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JUL 78 W B HARRISON, G HENDRICKSON, F JOHNSON DAAB07-77-C-0615

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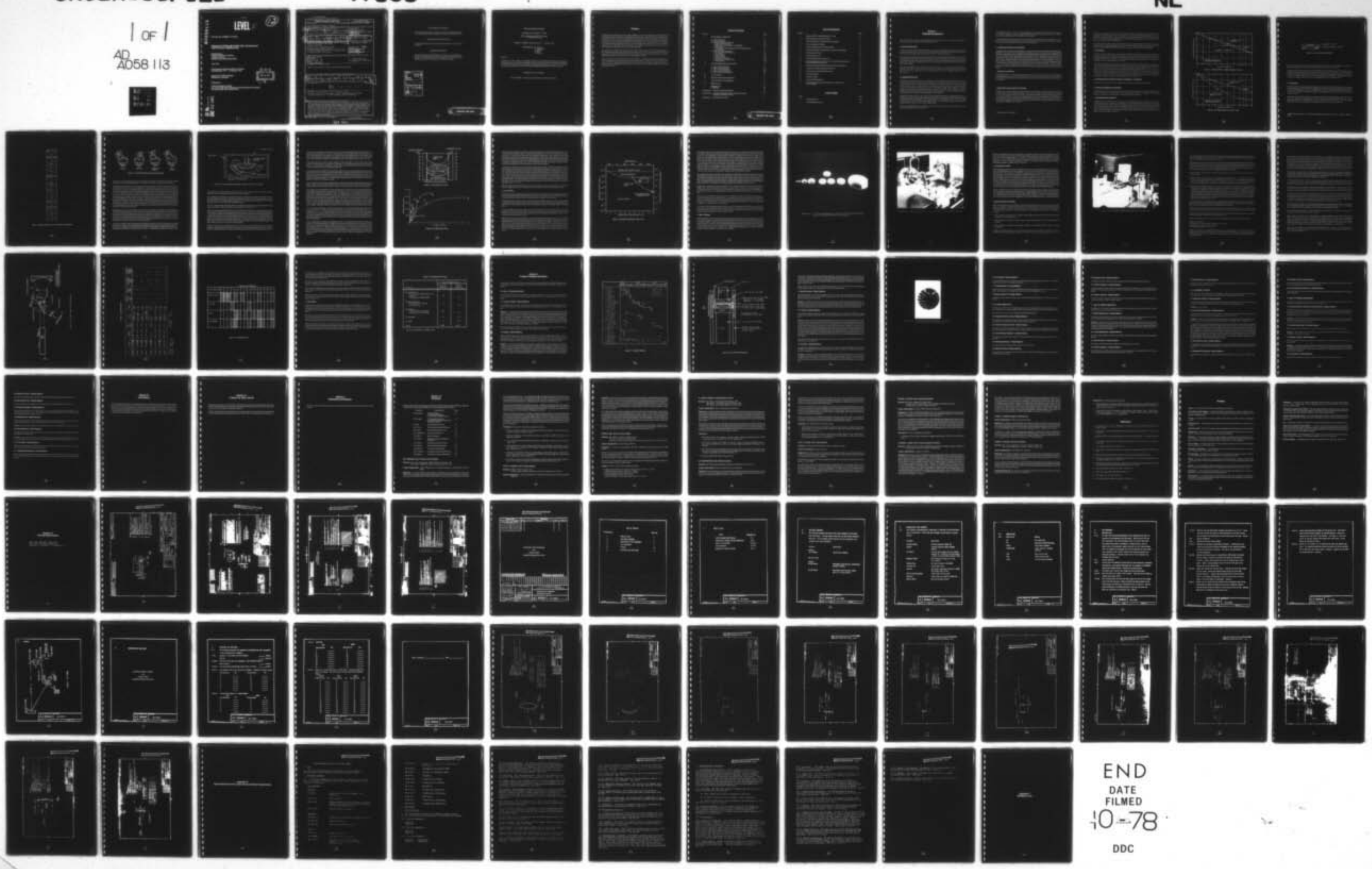

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Honeywell Inc.
Defense Electronics Division
Ceramics Center
Golden Valley, Minnesota 55422

July 1978

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This is the first quarterly report on the program, "Manufacturing Methods and Technology for Optical Fabrication." The program was initiated to develop low-cost techniques for the fabrication of germanium spheric and aspheric lenses and mirrors forFLIR optical systems. Several form-to shape lens fabrication techniques, including casting and hot deformation are being examined for their cost-saving potential. Examples of both materials have been obtained in this initial period of effort. The use of single point diamond turning of aspheric surfaces will also be examined after completion of an initial effort with flats produced by the various form-to-shape processes.

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FIRST QUARTERLY REPORT

CONTRACT NO. DAAB07-77-C-0615

Manufacturing Methods and Technology for Optical Fabrication

PERIOD COVERED: 28 September 1977 — 1 February 1978

PREPARED BY: W. Harrison
G. Hendrickson
F. Johnson
E. Able
J. Starling

OBJECT:

The objective of this contract is to establish cost-effective lens fabrication techniques for germanium operating in the 8-12 micrometer wavelength. All factors required to fabricate lenses with both spherical and aspherical surfaces such as tooling, material, forming time, finishing, and testing will be considered. Testing of each individual lens and the afocal and imaging FLIR assemblies will be performed.

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Purpose

This Manufacturing Methods and Technology (MM&T) contract was undertaken to establish improved methods for producing the spherical and aspheric germanium lenses required for Forward Looking Infrared (FLIR) systems. Current systems primarily use germanium elements with spherical surfaces that can be made by conventional lens fabrication techniques; however, such elements are very expensive. Germanium requires wasteful grinding and laborious finishing and inspection operations. In addition, conventional systems require more elements — a total of about nine, versus the six or seven used in an aspherical system. Efficient production techniques for aspherical optical surfaces, however, have not been available, and their high cost may limit their advantages.

By studying form-to-shape optical fabrication techniques that minimize the use of germanium and reduce final optical finishing, this program will determine cost-effective ways of producing both spherical and aspherical surfaces. Seven lenses and one mirror will be fabricated, assembled, and tested to meet the drawing and specification requirements given in Appendixes A and B.

The major milestones of this program consist of (1) delivery of samples produced by four different processes representing conventional and form-to-shape approaches; (2) delivery of 36 lenses made by the most cost-effective approach identified in Task 1; (3) delivery of four aspheric aluminum mirrors produced by single point diamond turning; and (4) delivery of eight sets of optical elements that have been assembled and tested.

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Section I
Engineering Approach

This section discusses the approach this program will take to determine more cost-effective methods for fabricating the optical elements required in FLIR systems.

A. DEVICE DESCRIPTION

A Forward Looking Infrared (FLIR) System is a thermal imaging approach of scanning for infrared emittance typically in the 3 to 5μm or 8 to 12μm region. This system has demonstrated its performance in a variety of day and night sensors for military surveillance and tracking systems.

The target being scanned emits a radiation signature that is amplified and then displayed on a real-time basis. Dual afocal telescope modules with a wide angle and narrow angle field of view for target acquisition and identification, respectively, concentrate the emittance to the IR imaging optics, which focus the signal on a cryogenically cooled detector array. A mirror scanning mechanism is also required to produce the complete display.

This particular MM&T program will focus on the needs for low-cost germanium optical fabrication approaches suitable for the afocal telescope and IR imager in FLIR systems where the number of lenses in the system have been minimized by the use of aspheric surfaces to produce a lighter weight, more compact system.

B. PROBLEM DEFINITION

The high cost associated with the optical components in present FLIR systems operated in the 8 to 12μm wavelength has and will be one of the primary limitations as to how extensively these systems will be developed by DOD. Dozens of different optical designs have evolved from the various developers of these systems. There is now a concentrated effort to modularize and reduce the variety of optical assemblies down to a few standard modules. Such an effort by the Army's Night Vision Laboratory on the IR imager has already been accomplished. However, each FLIR system still requires a different interchangeable pair of afocal telescopes for narrow angle and wide angle fields of view. Each of these telescopes contains about four optical lenses made primarily from germanium.

In addition to modularization, other workers have made significant progress in reducing the high cost associated with these optical systems. Aspherical surfaces have been utilized in a RPV (Remotely Piloted Vehicle) FLIR System to eliminate several spherical lenses.[1] Both substantial material cost and weight savings have been realized with this approach. The higher cost of producing aspheric surfaces, however, needs the further attention of this current MM&T effort.

The hot-forged, alkali halide lens forming process has also shown much promise toward being able to produce form-to-shape optical lens elements.[2]

It has also been shown[3,4,5] that two form-to-shape processes (casting and hot forming) for germanium are feasible. Production techniques for producing the dies and determining the limits and cost effectiveness of these capabilities must be established by this program.

Careful dimensional controls on the curvature, homogeneity, and thickness of each lens element are necessary to achieve maximum OTF performance of each assembly. Small deviation in uniformity could result in loss of system performance as seen on the real-time display.

C. DESIGN AND SPECIFICATION REVIEW

The germanium lens elements and assemblies covered by this contract are illustrated in the drawings in Appendix A. Each was reviewed during the proposal phase of this contract, and it was determined that the drawing requirements were not capable of meeting the Modulation Transfer Function (MTF) specification in the MMT 779845 specification dated 28 December 1976, "High Performance FLIR Lens and Lens Elements" reprinted as Appendix B. During the first portion of this program, considerable effort was spent on the computer evaluation of the lens and mirror assemblies to correct this problem. An error in the exponents for the sag equations was found, and these have been corrected in the drawings in Appendix A. While the lens and mirror elements now appear to be correct, other minor changes to the MTF specification or positioning of apertures and other adjustments may still be required to obtain maximum performance from the assemblies. Other comments on various paragraphs of these specifications are given below.

1. Design and Construction

Drawing SK-AB116-1* for an aluminum mirror specifies a honeycomb material and curved backing of undefined dimensions. We will use solid aluminum for a more economical material with a backing and mounting approach suitable for the assembly test cell to be built for evaluation of the optical elements in this assembly.

2. Edge Chips, Surface Quality, and Handling

Elimination of coarse grinding operations is expected to greatly improve the chip resistance, surface finish (scratches and digs), and general handling of these lenses. The surface finish of a diamond-turned lens or mirror cannot be measured by the present scratch dig method (MIL-O-13830). Where single point diamond turning (SPDT) is evaluated as a finishing operation for the infrared region, this specification is not applicable by nature of the operation and the relative insensitivity of the IR wavefront to these machine marks. Consequently, our evaluation approach for SPDT surface finishes produced under this program will be modified as discussed below.

*All drawings are in Appendix A.

Interference microscope measurements will be made of both the lenses and mirrors. A reflective optical system is now being built where surface irregularities, contours, and thin-film thickness may be measured with a vertical resolution of better than 0.25μm. Horizontal resolution in the object plane is better than 1.5μm. Results of these measurements will be compared with exiting data from diamond-turned surfaces to assess their relative finish quality.

Such measurements will be compared with the performance of lapped/polished samples for similar infrared applications using the techniques of Curcio.(6) As data becomes available, comparisons will also be made to other investigators' results where scatter is used as a measure of surface roughness.

3. Performance

In order to verify the applicability of the Optical Transfer Function (OTF) specifications as given in the proposal, the optics were computer ray traced and manufacturing allowances were added for Objective Assembly A and Objective Assembly B during the proposal effort. Both assemblies showed an MTF considerably below the design requirement. In addition, there appeared to be two aperture stops in Objective Assembly B that are not imaged onto one another.

After these discrepancies were examined by Honeywell with the Army at the beginning of the program, it was shown that changing the exponents of aspheric surfaces produced truer aspheric surfaces. Figures 1 and 2 show computer ray traces after the exponent change and a manufacturing allowance for each assembly for the on-axis and 10mm format requirements. Both assemblies appear to come very close to meeting the original specification for the on-axis situation. Assembly A was also satisfactory for this 10mm format; however, Assembly B is significantly lower in the 10mm format. It is recommended that the four curves in Figures 1 and 2 be used as a minimum specification for these situations. A significant design effort would be required to alter Assembly B for the 10mm format.

4. Workmanship, Environmental Conditions, Identification, and Marking

No radioactive materials in the AR coating of these lens and mirror elements will be used.

D. REVIEW OF FABRICATION PROCESS

In the following sections, the current process used for fabricating and testing Ge spheric and aspheric IR lenses is reviewed and compared with our proposed process. A typical flow diagram for the present process as understood at the beginning of the program is given in Figure 3.

1. Raw Materials and Purification

Currently, the lens fabricator has to procure Ge cylindrical blanks from a company such as Eagle-Pitcher Industries, Inc.* A typical 2.5-inch diameter by 1.0-inch thick blank of optical grade Ge currently costs about $190 in quantities of 100. In this analysis it is assumed that the blank is ground and polished to the final lens shape as discussed in the following sections. In our hot forming approaches, it will be shown that substantially less material, and thus less waste material salvage, can be realized. For instance, we expect to achieve a 25 to 50 percent cost saving on the material cost by using smaller optical blanks such as those shown in Figure 4.

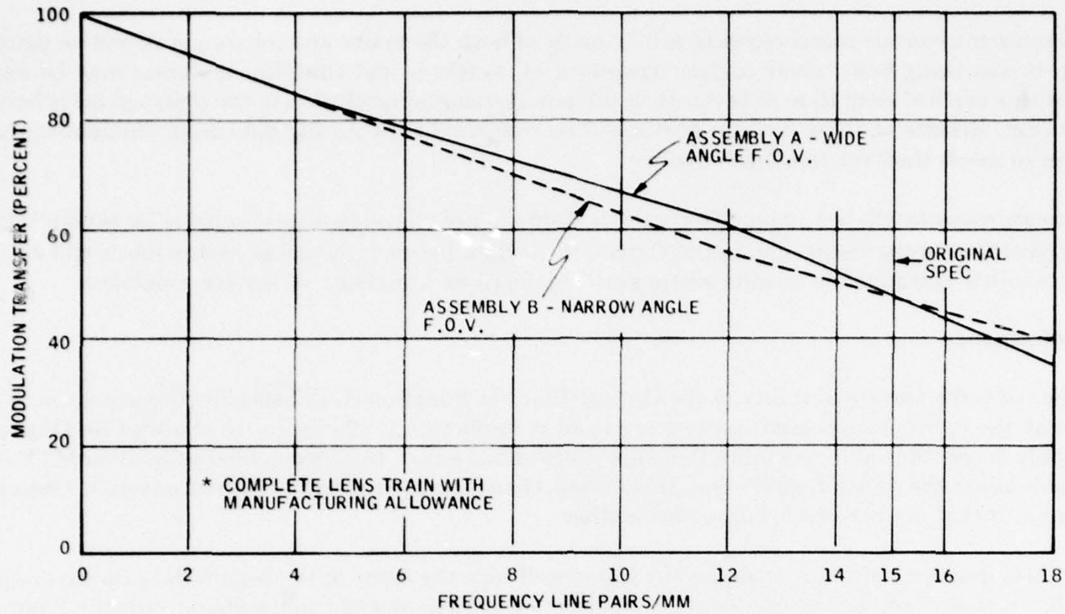

Figure 1. Objective MFT Vs. Spatial Frequency: on Axis

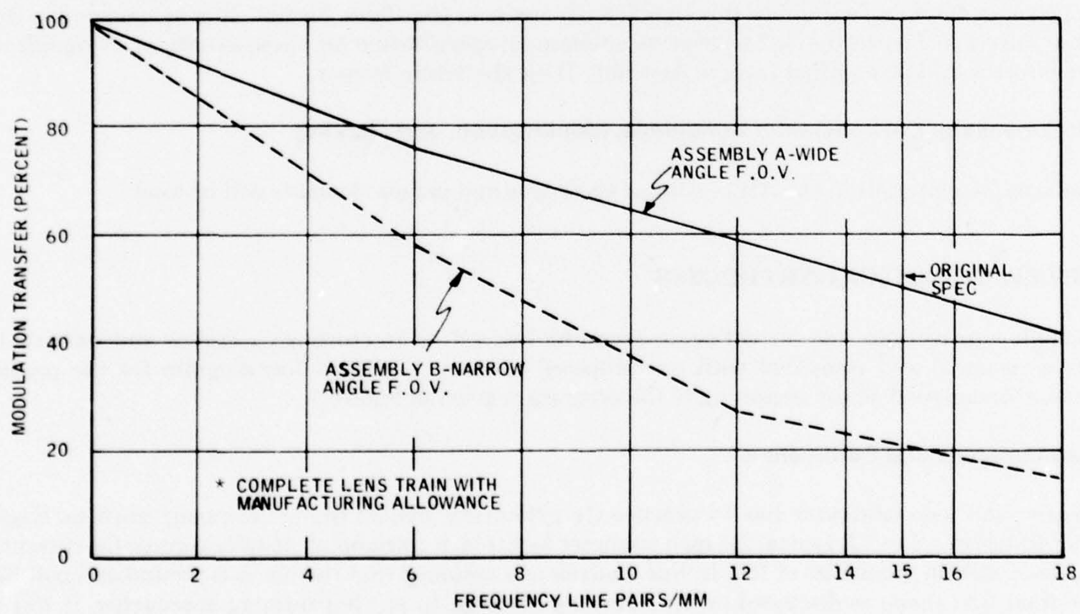

Figure 2. MFT Performance over 10mm Format

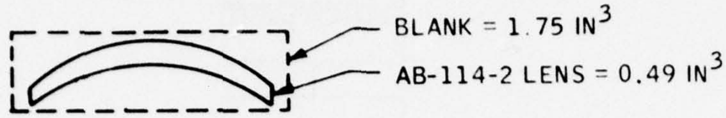

Figure 4. Lens Forming from Ge Blank

If powdered materials can be used, they will be melted and then casted to the approximate shape. The purity and doping level of the starting material will, of course, have to be controlled.

During the early 1950's a technique was developed for the casting purification of Ge to fabricate transistors and related semiconductor components. Ge in powder form was melted under closely controlled atmosphere and thermal conditions in a quartz boat. The ingot was subsequently chemically etched using a common CP-4 (HF, HNO^3, and acetic acid mixture) etchant and purified by zone refining in a multizone furnace. Single crystal growths were successfully produced on a production basis.

2. Lens Forming

Present methods of rough forming the lens shape start with a Ge cylindrical blank such as those indicated in drawing number SM-C-773478 (Appendix A). As shown in Figure 4, a typical blank such as that required for the SK-AB114-2 lens uses less than 30 percent of the Ge in this blank. While scrap material is commonly reclaimed, its collection is expensive, only partially recovered, and only 85 percent of its value is recovered.

The present method of generating a lens from the Ge blank is to use grinding tools to take off the major part of the material. A cup grinding tool is spun by one shaft while the Ge blank is spun by a second shaft. Depending on where the spin axes cross, the surface generated will be convex or concave, and the radius of curvature is controlled by the inclination of the two axes, as shown in Figure 5.

*Eagle-Pitcher Industries, Inc., Compounds and Metals Department, PO Box 737, Quapaw, Oklahoma 74362.

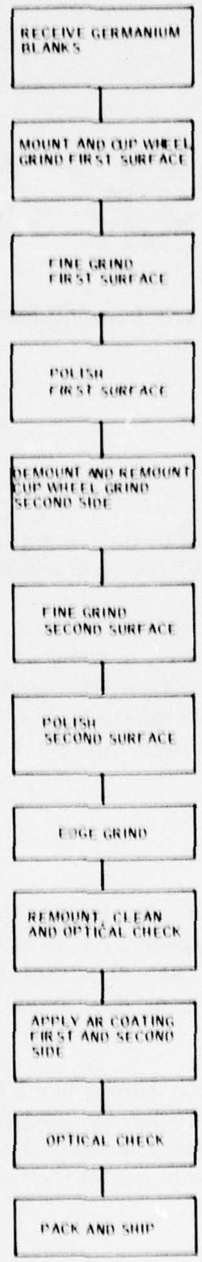

Figure 3. Present Germanium Lens Fabrication Flow Diagram

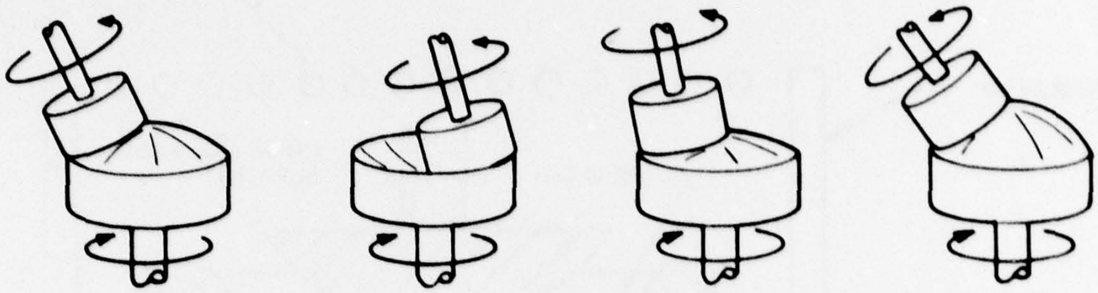

Figure 5. Conventional Methods of Generating Lenses

The surfaces are then brought close to the desired radius and diameter by grinding and then fine grinding with cast iron tools and diminishing grit sizes of abrasive. The surface is then ready for polishing.

In this program three hot form-to-shape approaches will be compared with the conventional method described above. Not only do we expect a significant cost advantage to result from these form-to-shape approaches, but we expect a substantial performance improvement. This will result from the fact that the conventional approaches described above induce significant surface damage into the Ge. Ground surfaces may have a rupture stress as low as 7000 psi.[7] Polishing may improve the rupture stress to about 15,000 psi, but the extent of this improvement is directly related to how much material is removed. Material cast to shape or hot worked to shape will contain minimal surface damage, and only slight mechanical or chemical polishing will increase the strength to about 16,000 psi. At least one of the hot forming approaches described below should produce high-strength optical blanks very close to the final shape required and, at a minimum, eliminate the need for rough shape grinding. Thus, substantial material and cost savings associated with the rough grinding operations should be realized. Casting of Ge lens shapes in molds should be the most direct approach available for minimizing the total effort involved in the production of close-tolerance lens blanks.

A diagram of a two-zone vacuum furnace for in situ lens casting is shown in Figure 6. With this approach, the starting material, either Ge powder or chunks, is first melted in the mold and then cooled from the bottom until the desired temperature gradient is established by independent power adjustment of the upper and lower heating elements. This promotes unidirectional solidification, ensuring that solidification begins at the mold bottom and proceeds upward so that the final material to solidify is at the top surface. If the free surface of the melt is allowed to solidify before the interior, the expansion of Ge upon solidification will cause the ingot to crack, or grossly distort.

The melt is cooled at rates slow enough so that impurity materials, voids, and inclusions are excluded from the ingot. However, the slowest possible cooling rate will not produce the most desirable material. A fine grain size, produced by more rapid cooling, will give the blanks greater strength and avoid the 11 μm absorption band observed in single-crystal Ge.[8] Thus, a compromise intermediate cooling rate that

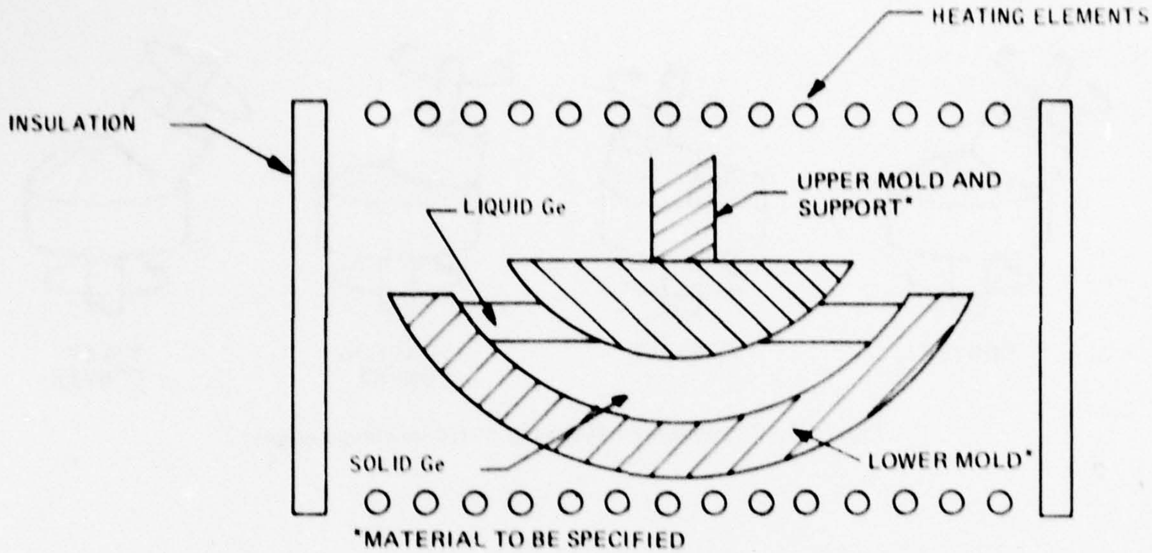

Figure 6. Furnace and Mold for Casting Concave-Convex Ge Lens Blanks

simultaneously yields acceptable microstructure, purity, and continuity will be used. These process parameters will be established during the period of this program.

After solidification of the blank is completed, the power to the heaters is readjusted to minimize the temperature gradient between the center and edge. The blank is then cooled to room temperature at an appropriate schedule to avoid high residual stresses and accompanying optical birefringence. Stress relief by plastic flow also occurs in the plastic temperature region.

This basic casting technique has been shown to be applicable to formation of optical blanks from a wide range of materials, among them alkaline earth fluorides[10] and silicon.[13]

There are some fundamental difficulties to be dealt with in the casting of Ge, as with the casting of optical material. Many potential mold materials will be eliminated from consideration due to their slight solubility in molten Ge. However, the low melting point of Ge makes a wide range of mold materials available. It is expected that many of these will be semipermanent and only require an occasional refinishing and cleaning. This will be easy for spherical surfaces but present more of a problem for aspherical surfaces. Quartz is an acceptable mold material in this respect. A sticking problem between solidified Ge and the quartz material can be overcome by depositing a thin layer of carbon on the mold. Alumina, mullite, and glassy carbon may also be acceptable as mold materials.

Ideally, the outer part of the mold, adjacent to the convex face of the lens blank, will have a thermal expansion coefficient less than that of Ge, so that upon cooling the lens blank will have contracted more than the mold and release from it. Quartz should be a good mold material for this application. Likewise,

the part of the mold adjacent to the concave face of the lens blank should have a thermal expansion coefficient greater than that of Ge, so that it contracts away from the blank during cooling. Alumina is a possible mold material for this application. It should be noted that large numbers of such shapes can be cast as described above, and that zone refinement by directional solidification can be accomplished in such a manner that the impurities are concentrated in the noncritical mounting region of the lens.

Those lenses that have a fairly uniform thickness, such as SK-AB115-2, may be most economically formed by hot deformation of a sliced disc of Ge (Figure 7). The temperature associated with this process will be lower than those encountered in casting; therefore, improved surface finish and dimensional control is expected from this hot deformation process.

In an expired patent, Gallagher[4] has shown that single crystal Ge can be plastically deformed at temperatures above 670°C to as high as 50 percent deformation as shown in Figure 8. Similarly, single crystal silicon can be deformed at temperatures of about 1100°C. Honeywell has verified that silicon, the more difficult material, can be deformed. A silicon wafer 0.040-inch thick was hot deformed at 1390°C in an argon gas atmosphere. Similarly, recrystallized alkali halide lenses have been produced at Honeywell by Bernal[2] with the hot deformation process.

This current program will evaluate the feasibility of this process by producing hot deformed cylindrical blanks of single crystal and polycrystalline (cast) Ge. Each of these materials will be hot deformed into larger diameter cylindrical blanks with up to about 50 percent reduction in their original thickness.

Ge is brittle at room temperature, but it has been known for some time that this covalently bonded material readily deforms at elevated temperatures.[4,10] Since the major point of this discussion relates to the feasibility of forging Ge into shapes suitable for IR optical elements, a comparison of the deformation behavior of Ge and the alkali halides is in order. The alkali halides (e.g., KCl) are also brittle at room temperature but have been quite successfully forged into IR optical elements at elevated temperatures.[2] Materials with the rock salt structure slip on {110} <110> systems at room temperature. Only two of the {110} <110> slip systems are independent, and five are needed to maintain strain continuity during forging.[11] Thus the alkali halides must be worked at high temperatures where slip also occurs on {100} <110> systems. The added slip systems provide the five necessary for strain continuity, and the billets can be forged to high strains without fracturing.[2] This is why alkali halide optical elements are forged.

In Ge the situation is different. Ge has the diamond cubic crystal structure and deforms by slip on {111} <110> systems,[11] i.e., the same slip systems that operate in face centered cubic metals. There are 12 independent {111} <111> systems and strain continuity is not a problem. Ge is brittle at room temperature because of the strong covalent bonding in the structure. The lattice resistance to the propagation of dislocations is high and the yield stress at ordinary temperatures generally exceeds the fracture stress. At elevated temperatures, however, the resistance is overcome by thermal activation and the material can be plastically deformed.

Ge can be deformed at temperatures exceeding about 500°C. Two predominant deformation mechanisms operate in Ge at high temperatures. At high strain rates and stresses deformation occurs by the conservative motion of dislocations by glide through the lattice. In Ge, the stress above which deformation occurs only by glide is about 10^{-2} G, where G is the shear modulus[12] or 75,400 psi. At stresses lower than this and at strain rates usually encountered in slow forging operation, Ge most likely deforms by dislocation creep.[12] In dislocation creep, deformation results from dislocation glide and diffusion-controlled climb around obstacles.[12,13] The deformed microstructure consists of dislocations aggregated into cells or subgrains.

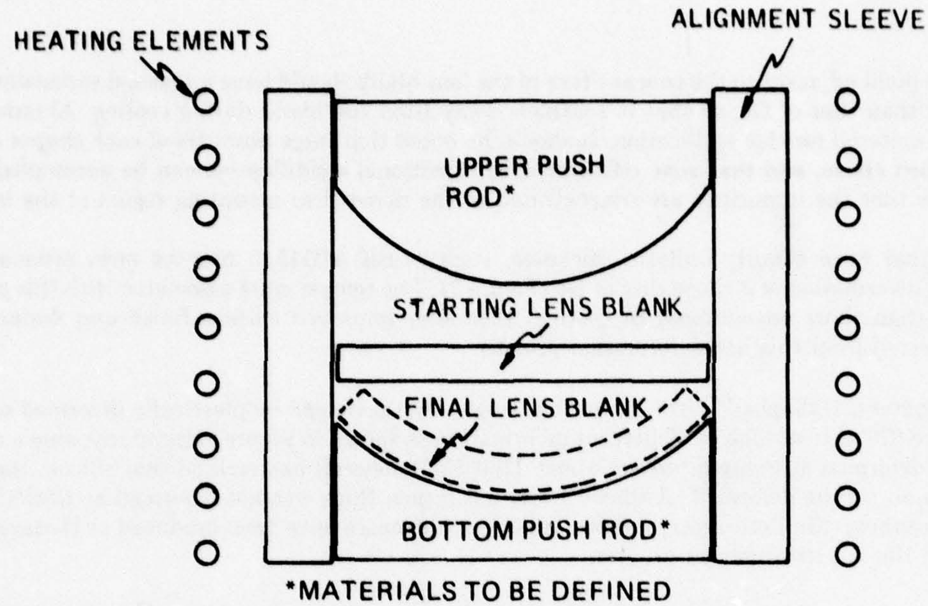

Figure 7. Hot Deformation of Lens

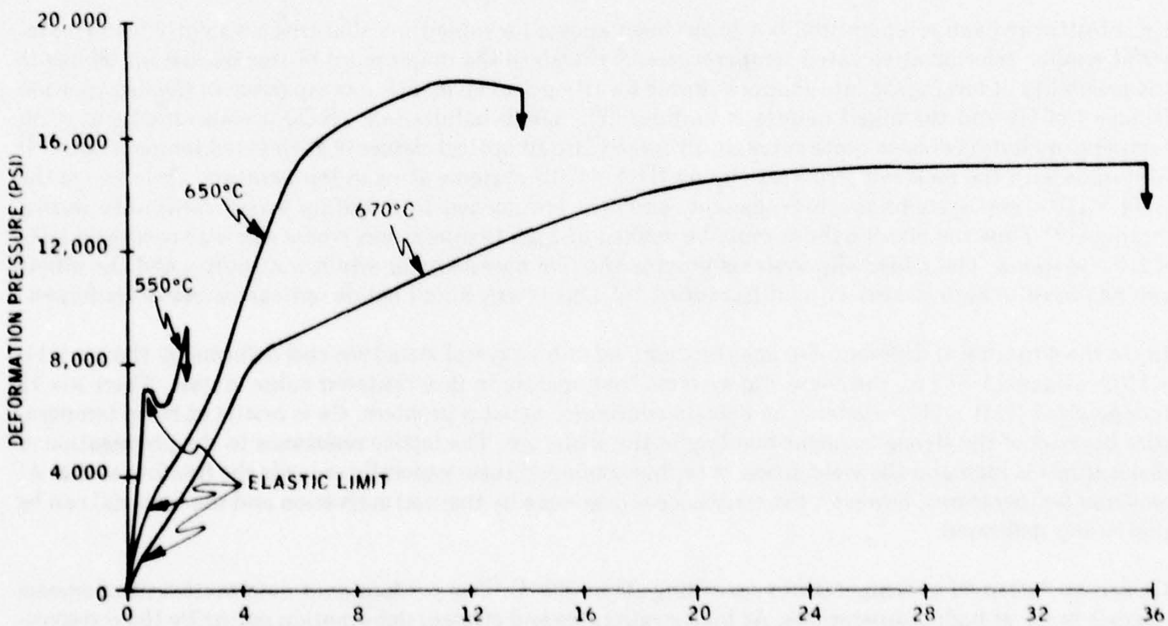

Figure 8. Hot Deformation of Ge

The deformation mechanism operating in a material at different strain rates and temperatures is conveniently illustrated with the aid of a "deformation mechanism map."[12,13] In such a map, the normalized stress, σ/G, is plotted as a function of the homologous temperature, T/T_{mp}, where T is the working temperature and T_{mp} is the melting point both in degrees absolute. The stress-temperature space of the map is then divided into regions in which a single deformation mechanism is rate controlling or dominant. Also plotted on the map are contours of constant steady-state strain rate. Thus for any material for which a deformation mechanism map exists, one can determine the steady-state strain rate and dominant deformation mechanism for any combination of stress and temperature.

A deformation mechanism map for Ge is shown in Figure 9 from Ashby.[12] Only one strain rate contour line is shown on the map. This is the bottom line on the figure and separates the elastic regime (where no plastic-deformation is expected) from areas in stress-temperature space where deformation occurs by, e.g., dislocation glide and dislocation creep. Each deformation mechanism map depends on the sensitivity of the microstructure. The one shown here has been developed for polycrystalline Ge with a grain size of 32μm. The cross-hatched area on the map indicates the range of stresses and temperatures anticipated during forging. The stress range is from 10,000 psi to about 50,000 psi, and the temperature range is from 600 to 800°C. Note that under these conditions the dominant deformation is by dislocation creep. Although not shown on the figure, the steady-state strain rates in the cross-hatched region are probably in the range of 10^{-6} to 10^{-2} sec^{-1}.

Residual stresses from the hot deformation process may introduce optical nonuniformity to the bulk Ge; however, annealing on the lens cooling cycle can be employed to relieve these residual stresses.

3. Lens Finishing

After the lens curvature has been generated by the currently used rough grinding and lapping operations, the surface damage produced must be removed. The final lens thickness, finish, and optical figure must be simultaneously generated during this final polishing or diamond turning operation.

Polishing of the lens is done on a low viscosity tar pitch lap using fine alumina or cerium oxide polishing compounds. The lap material is chosen to be soft enough to conform to the surface being generated, but not so soft as to smear the germanium. Waxes, such as beeswax, are used for bonding of lenses to blocking plates.

From the standpoint of thermal stability, the cutting speeds, lubricants, and lubricant flow rates should be similar to those used for glass; that is, the rate of heat generation during polishing and the thermal deformation characteristics of the lens material indicate that germanium is equivalent or superior to visible-region optical glass in these respects.

Spherical surface lenses with large radii are commonly gang-polished in groups of three or more, depending upon the size of equipment available and the radius being generated. Highly curved elements must be polished individually or on multiple spindle machines. Aspherical lens shapes can be done only one at a time, or at best, on multiple spindle machines using compliant laps. Due to the constantly changing polishing characteristics of the compounds and the lack of true conformance over the required area of the lap, much individual hand polishing is normally required for aspherical lenses, producing higher fabrication costs. Cleaning of polished lenses is performed in a vapor degreaser using trichloroethylene or other solvent.

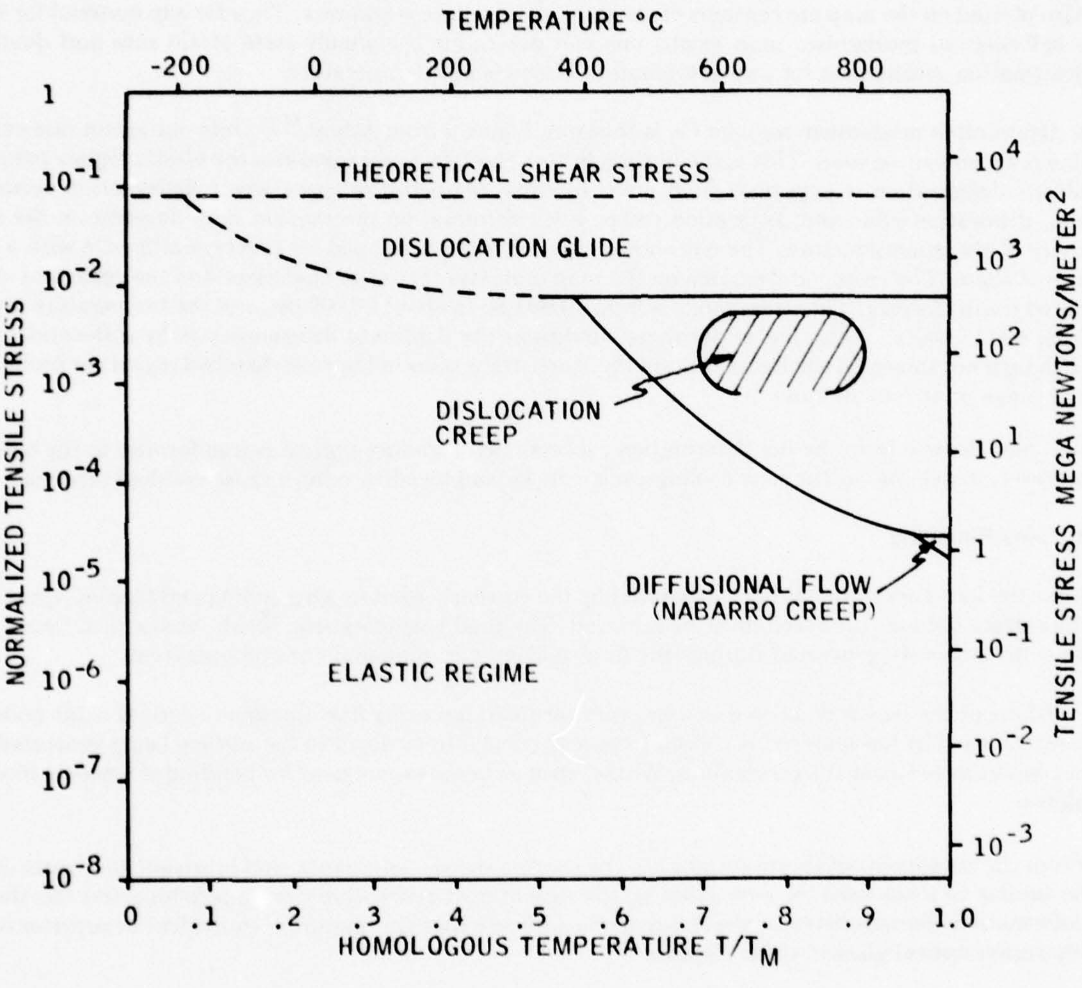

Figure 9. Deformation Mechanism Map for Ge

Our proposed approach in this program will minimize the amount of material removed during the finishing operations. We have purchased a six-spindle lens polishing machine where the speed of each spindle, the motion of each lapping arm, and the pressure applied to the lap are all controlled by a single control power-drive. All parts being produced therefore "see" the same polishing action and presumably result in identical surface figures. Thus, optical monitoring of one surface being produced on one spindle reasonably assures the operator that all other parts are the same. Numerical control from the optical monitor to the central power-drive will consequently supply feedback to all spindles. While this more automated approach appears to be the most cost-effective approach for generating spherical and slight (five-fringe) aspherical surfaces, strong aspheric surfaces will probably be best generated by numerically controlled single point diamond-turning (SPDT) equipment. Establishment of the optimum finishing process (diamond turning by itself, or followed by the automatic lapping operation for this production-type fabrication in Ge) will constitute an important, significant part of this MM&T program.

The applicability of diamond turning to the generation of infrared optical quality surfaces in Ge has been demonstrated by Johnson and Saito.(1) In this program, conducted for the Air Force Materials Laboratory (AFML), Rank Optics Ltd. fabricated a diamond-turned Ge aspheric detector-lens using their standard two-step technique: figuring on their R-θ turning machine, then performing a post-turning, automatic compliant lap final polish. Performance testing of this element satisfied system design goals for spot-size and OTF, as measured by the Tropel Model 2000 computerized OTF system.

Under a follow-on program (Contract AF33615-76-C-5243), Bell and Howell fabricated a wide-field Ge aspheric lens. Their three-axis Moore Machine was used without the need for a post-polishing operation. Testing of this element is still in process and will provide a valuable technology input to this MM&T program. Figure 10 shows a few of the diamond-turned Ge lenses that have been produced for various IR systems.

The advantages provided by the application of N/C diamond turning to the production fabrication procedure for infrared optical components center on the inherent accuracy and repeatability of the process. Not only can these characteristics be brought to bear for the simpler spheric surfaces, but aspheric components can be produced where conventional finishing difficulties would almost eliminate consideration of aspherics as a production system component.

The introduction of generalized aspheric surfaces into system designs will normally permit a savings of an average of one optical element per such surface. Thus the inherent advantage of N/C diamond turning will be to permit the designer access to general aspheric elements for production systems, and thereby permit savings in components, volume, weight, and cost.

4. Mirror Finishing

While the technique of N/C diamond turning has not progressed to production requirements for Ge lenses, this capability has been demonstrated on a production scale for flat and contoured infrared mirrors. Production capability for flat surface diamond machining is now being demonstrated at Honeywell, as shown in Figure 11 on the AN/AAD-5 Infrared Reconnaissance Set production program. This figure shows a four-axis spin mirror with each optical surface being machined to within ±4 arc seconds of its adjacent surface. All surfaces are flat to less than 1/10 λ. Ongoing Honeywell programs are working toward the extension of this capability to contoured mirror surfaces.

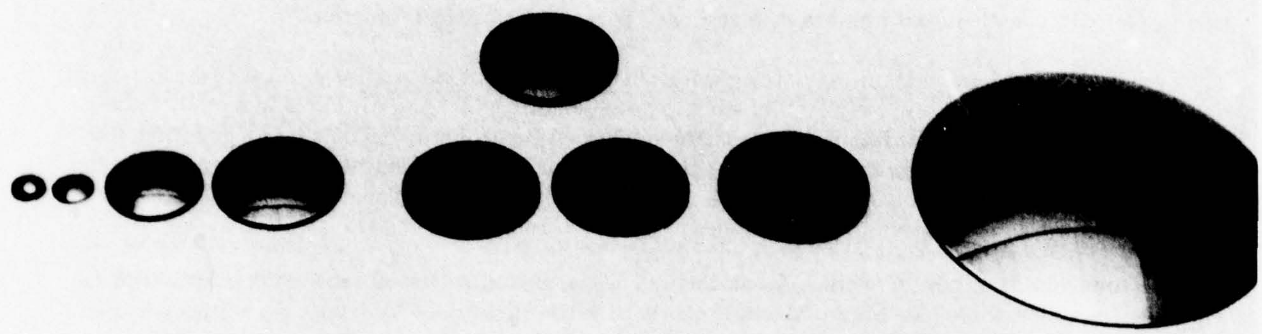

Figure 10. Ge Lenses Machined on a Two-Axis N/C Diamond Turning Lathe for Honeywell FLIR-Type Programs

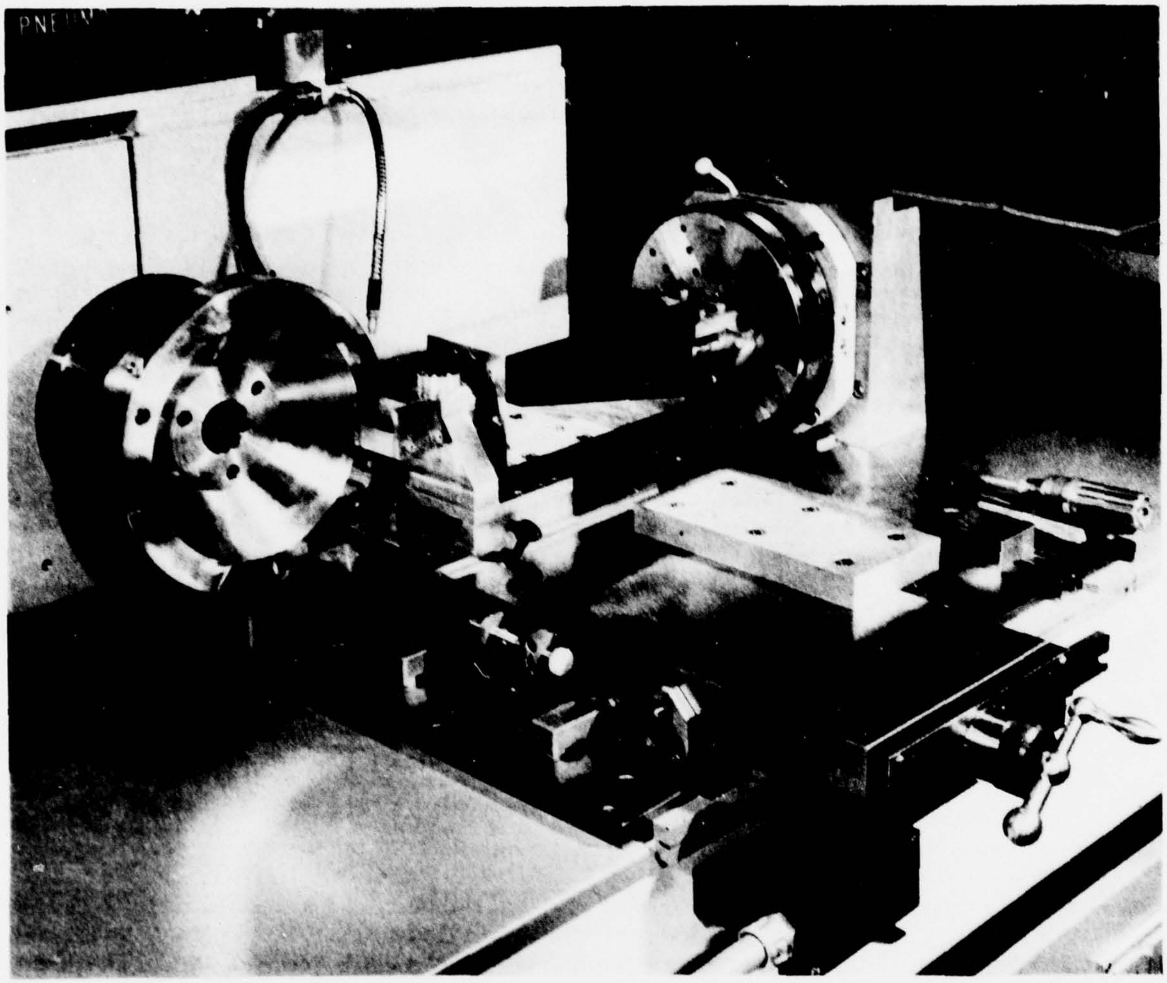

Figure 11. Single Point Diamond Turning (SPDT) of Four-Surface Mirror

Recent encouraging results at the University of California's Lawrence Livermore Laboratory (LLL) have shown that because the Moore N/C diamond-turning machines are extremely repeatable, their periodic errors can be "programmed-out." By "survey" measuring and accurately recording the errors with respect to "x" and "y" slide travel, the reverse sign can be programmed into the machine tool's computer. Honeywell is currently working with Moore to combine its computer expertise with Moore's precision machining experience to improve the N/C function.

5. Antireflective Coatings

While this program does not intend to establish more cost-effective AR coating approaches, one of Honeywell's existing broadband AR coating designs for Ge will be used on all fabrication test blanks and prototype lens parts. These coatings are required to maximize the optical transmission through the system. The high refractive index of Ge causes almost 40 percent reflection at each surface. Thus, AR coatings are a very necessary part of IR optical systems using Ge. In addition, they environmentally protect the polished surface of each lens to stabilize its optical performance over long periods of time. The requirements of MLAR 306 type coatings for Ge can be met within the existing capability in production. This should be an integral part of the facility doing the final polishing of each element. The elimination of an intermediate transfer of the polished material decreases the chance for coating damage that may otherwise result from more extensive handling. Automation of the AR coating process and minimization of the number of layers in the AR coating design should be future goals of other MM&T programs.

Extensive work in the area of coatings for Ge has been performed and the technology base and general coating experience for producing coatings exists. A present program (Contract F33615-77-C-5057) to develop multilayer thin film coatings to laser harden missile and FLIR optical trains will address the problem of AR coating Ge in the 8 to 12μm region. This program is expected to provide valuable experience in AR coating Ge that will be directly applicable to this current MM&T program on optical fabrication.

6. Optical Assembly and Testing

While the establishment of cost-effective optical assembly techniques is beyond the scope of this program, it is necessary to assemble the lenses and mirrors from Tasks 2.0 and 3.0 and obtain their assembled optical performance. Tests and measurements at specified stages of construction will be made to assess their quality and ability to meet general infrared system requirements. These tests are categorized as follows:

- Those required to determine the suitability of prefinished lens elements whose figures are thermally formed close to final dimensions.

- Those required to determine surface accuracy during final finishing and while still mounted for finishing.

- Those required to determine lens element suitability as measured through assembly or system performance.

Initially, flat samples produced by each of the form-to-shape processes shall be measured to assess the suitability of their bulk properties. Significant, bulk defects can effect optical performance in two ways:

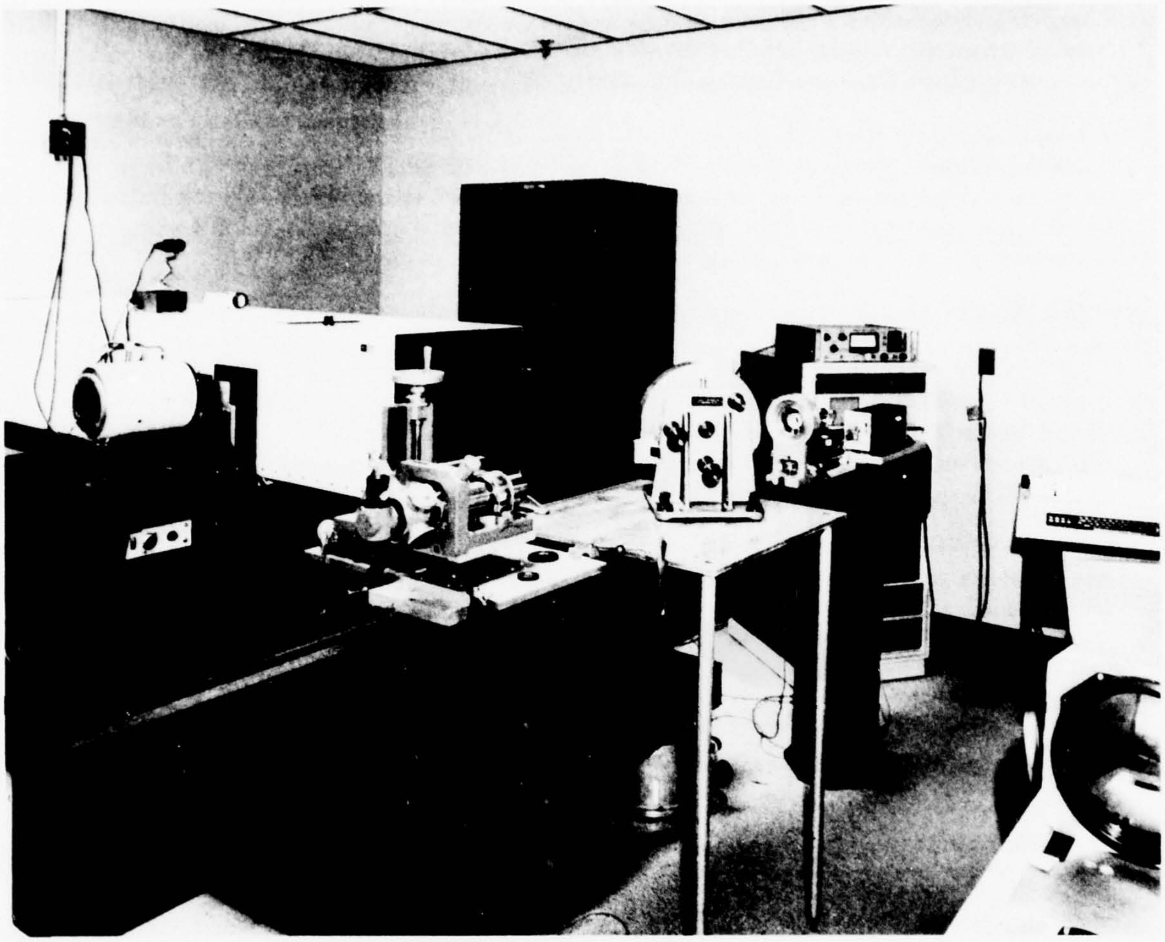

Figure 12. Computer-Automated OTF Lens Test Facility

(1) Large inhomogeneities of refractive index can perturb the wavefront and thereby degrade the ability to form sharp images, and (2) critical scatter centers may cause some of the radiation in transmission to spread over the field, causing a decrease in contrast.

The bulk properties of the Ge elements must be demonstrated as being suitable for infrared applications independent of their surface properties. In addition to indicating the presence of performance degradation due to the bulk properties of the material, information concerning the mechanism involved may be necessary. If so, an iterative technique for process improvement will be used. Three existing tests to isolate the bulk and surface properties are available for this process analysis:

- visible (6328A) interferometric techniques will be utilized to assess the surface characteristics of the lens elements.

- Infrared (10.6μm) interferometry will be performed by Honeywell in cooperation with Dr. James Wyant, of the University of Arizona's Optical Sciences Center, on the process samples and on the specified lens assemblies. These test results, in conjunction with the surface wavefront characteristics from test (1), will present the wavefront distortion introduced by the bulk material defects.

- Infrared optical transfer function (OTF) measurements will be performed using the Tropel Model 2000 automatic OTF (Optical Transfer Function) Lens Testing System (Figure 12), modified for 8-12μm performance, on the process samples and the lens assemblies. This system is available and specifically built for testing FLIR components. Information from these tests, in addition to quantifying assembly spatial frequency response, will assist in identifying the type of bulk defects present, if any; that is, those due to index variations from those due to forward scattering phenomenon. Present in-house capability will also allow the measurement of 10.6μm scatter on the initial fabrication test samples to quantify their bulk and surface scatter.

As shown in Figure 12, modifications to the Tropel Model 2000 OTF Tester to permit 8-12μm IR measurement have already been made and include a blackbody source, 8-12μ spectral filter, an IR collimator with all reflective optics, and a Reader thermopile detector assembly.

Additional testing will be performed to measure material electrical resistivity, optical absorption, and mechanical strength to thoroughly define the uniformity of material produced by the various processes.

The surface figure of the lens elements will be monitored during the final finishing operation to minimize the time required for iterating the test and finish sequence.

There are four alternate ways of testing surface figure applicable to spheric and aspheric figures:

- spherical test plates
- Interferometry, using a synthetic hologram as a reference
- Interferometry using a null corrector lens
- Profile measurement by stylus contact

Spherical test plates are appropriate for spherical or near spherical figures. This method is simple, economical, and conventional. It is based on the interference of radiation between a spherical sample and the spherical test plate, which is sufficiently close in shape to provide interference defining differences of a few visible waves.

The LUPI (Laser Unequal Path Interferometer), Figure 13, is a modified Twyman-Green interferometer. It uses a helium-neon laser as a light source so that it has the capability of working at widely unequal optical paths in the test and reference arms. The modification from Twyman-Green is a converging lens in the test arm. This changes the plane wavefront to spherical. This spherical wavefront comes to a focus and if placed at the center of curvature of a sphere, or in the image plane of an optical system set up for autocollimation, the wavefront will go through the system and return to the beamsplitted where it is re-combined with the reference wavefront. Any aberrations produced on this wavefront by the system will show up as fringes of equal optical path difference (OPD) and is a measure of the quality of the system.

Interferometric systems such as a LUPI can be used with a null corrector or a synthetic hologram for measurement of a spheric surface which departs from a sphere by an amount significantly exceeding five visible waves. In general, synthetic holograms are much less expensive than null correctors. However, for a large production run, null correctors might be cost effective.

For severe aspheric surfaces, wavefront correction by synthetic holograms or null correctors may not be cost effective. In this case, surface measurement through the use of low contact pressure stylus can be made. Such an approach would be practical and easily adapted to the initial on-machine measurements.

The application of interferometric methods involves different implementation considerations for convex and concave surfaces, though the principle remains the same. In the case of a concave surface, a small laser beam and a microscope objective provides a focus near the center of curvature of the best fit sphere.

The sample surface then refocuses the image near this center of curvature for subsequent interference with the reference wavefront in the interferometer. In the case of a convex surface, the laser beam must be expanded and converged by an auxiliary lens onto the sample surface. The convergence must be such as to focus at the center of curvature of the best fit sphere. The return beam is then recollimated and returned to the interferometer for subsequent interference with the reference beam.

The dimensions of the specific elements defined in Appendix A are summarized in Table 1. Note that of the seven aspheric elements, two surfaces are aspheric but small enough difference with a best fit sphere that, although identified as aspheric, could be tested with a spherical test plate.

The remaining aspheric surfaces would preferably be tested with a synthetic hologram as a reference, but could also be tested with null correctors or a stylus.

Figure 14 shows a summary matrix defining the test method applicable to each surface referenced in Table 1. The basis of selection is to use a spherical test plate for all convex spherical or near spherical surfaces and a LUPI for all concave spherical or near spherical surfaces. Actually, either test method is applicable to both types of surfaces, but this assignment allows minimum surface contact, while keeping within the guidelines of existing test equipment. If the LUPI were used for convex surfaces, an accurate converging lens would have to be constructed and the system modified to accommodate it.

In the case of the aspheric surfaces of SK-AB 108-2 and SK-AB 115-1, either a synthetic hologram or a stylus could be used and are included in the matrix. Null correctors, while technically suitable, would be more costly for this program.

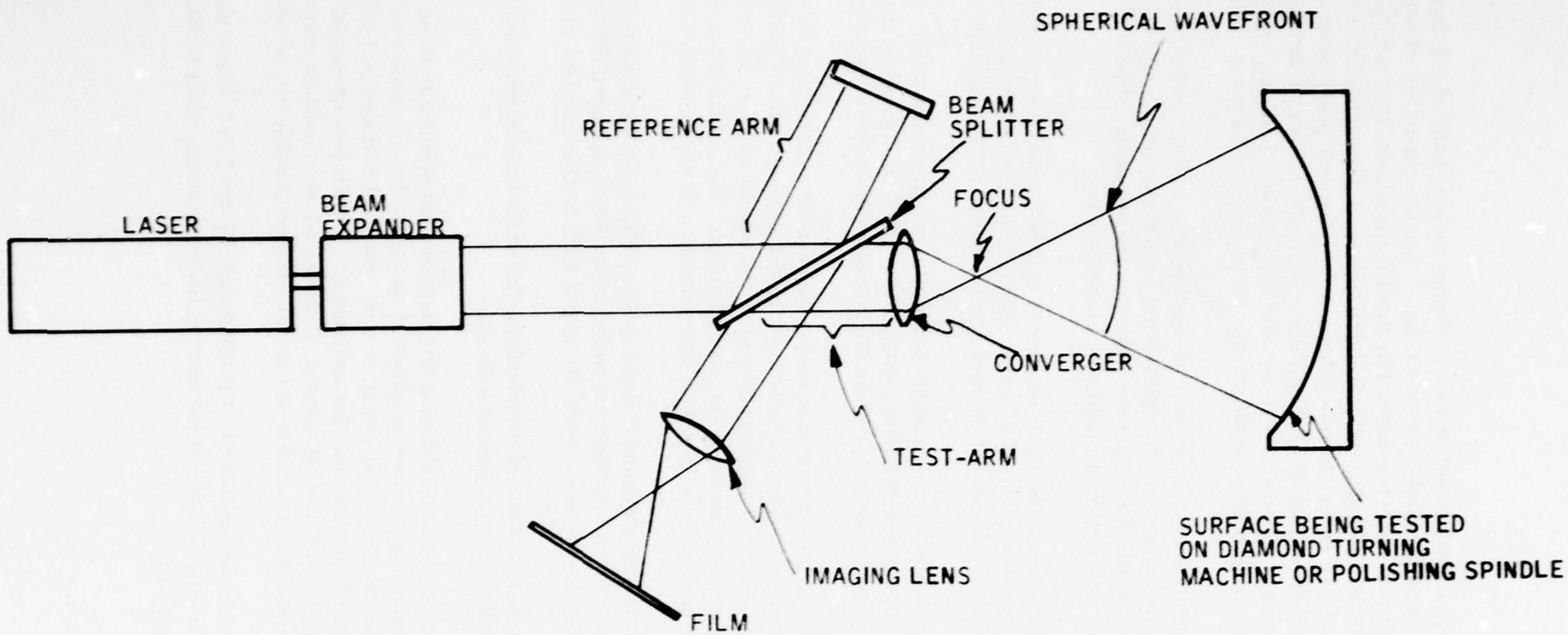

Figure 13. LUPI (Laser Unequal Path Interferometer)

Table 1. Lens Specification

Lens	Diameter (inches)	Center Thickness (inches)	Minimum Clear Aperture (inches)	Spherical Radius (inches)	Surface Key/No.	Maximum Test Plate Fit Fringes at 6328Å	Maximum Astig. Fringes at 6328Å	Best Fit Spherical Radius for Aspheric Surface inches	Spherical Maximum Departure Fringes at 6328Å
AB114-1	2.600 $^{+0.000}_{-0.002}$	0.200 ± 0.002	2.400	Aspheric 3.0197 ± 0.0002	$5/R_1$ $6/R_2$	4	2	2.6499	24
AB114-2	1.800 $^{+0.000}_{-0.002}$	0.192 ± 0.002	1.600	1.310 ± 0.008 1.411 ± 0.008	$7/R_1$ $8/R_2$	4 4	2 2		
AB115-1	2.000 $^{+0.000}_{-0.002}$	0.100 ± 0.002	1.800	Aspheric 1.008 ± 0.008	$9/R_1$ $10/R_2$	4	2	1.2203	53
AB115-2	2.000 $^{+0.000}_{-0.002}$	0.190 ± 0.002	1.800	-1.6919 $^{+0.0000}_{-0.0008}$ Aspheric	$11/R_1$ $12/R_2$	4	2	-1.6727	5.6
AB116-1	6.200 $^{+0.000}_{-0.002}$	0.80 min	6.000	Aspheric Mirror	$13/R_1$			-16.1031	30
AB116-2	2.50 ± 0.02	0.250 ± 0.002	2.30	-6.1883 ± 0.0008 Aspheric	$15/R_1$ $16/R_2$	4	2	-3.6434	24
AB108-1	3.260 $^{+0.000}_{-0.002}$	0.300 ± 0.002	3.00	Aspheric -41.250 ± 0.08	$1/R_1$ $2/R_2$	4	2	41.2901	3.6
AB108-2	1.000 ± 0.001	0.110 ± 0.005	0.90	2.153 ± 0.002 Aspheric	$3/R_1$ $4/R_2$	5	2	2.4035	89

Chamfer 45° ± 5°
Face Width 0.020 ± 0.010
Centering ± 0.0005 FIR

Surface Finish 80/50
AR Coating MLAR 306

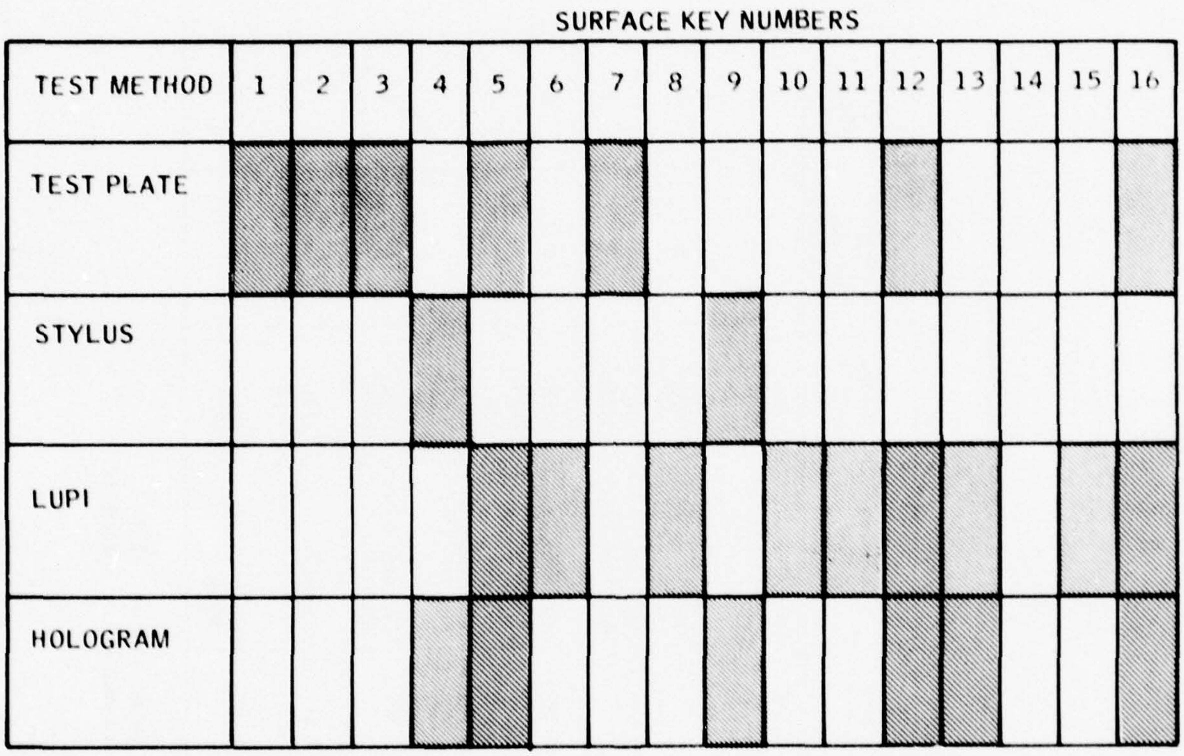

Figure 14. Test Method Matrix

The testing of two assemblies for assessment of system performance will be performed on the two assemblies identified as Objective Assembly A and Objective Assembly B. Objective Assembly A consists of a wide-angle afocal assembly with an IR imager; Objective Assembly B consists of a narrow-angle afocal assembly with the same IR imager.

One Type A and one Type B test cell will be built and eight sets of the identified assemblies will be evaluated for compliance with the specified field of view, aperture, MTF, linear distortion, and optical transmittance in accordance with Section 4.6 of the specification (Appendix B).

Linear distortion and field of view measurements, which are based on relating field angle with image location, will be measured with the same fixturing available with the Tropel automatic OTF measuring equipment.

Optical transmittance will be measured with coated witness samples. Adherence, abrasion, humidity, and salt spray tests shall be performed in accordance with the specification drawings and on the coating witness samples only.

7. Cost Analysis

The potential cost savings that can result from this MM&T program are very significant. Based on a production rate of 1000 lenses per month and an average lens (SK-AB 115-2), we estimated at the start of this program that an uncoated lens produced by conventional approaches would cost $458 each, as opposed to $202 each for those produced by the hot forming approach. Table 2 shows the basis for these estimates.

The largest potential saving should be realized in surface finishing; however, much of this saving is generated by the fact that the hot formed lens is very close to its final shape. Other significant savings occur in the Ge used (hot forming consumes less than 50 percent) and the rough forming operation. The cost of the initial tooling and its maintenance are higher for the hot forming method.

Based on this projected savings for an average type lens and an estimate that 24,000 lenses per year will be used, the Army could save about $6 million per year. Other savings from the diamond turning of mirrors based on 3000 per year should amount to about $100 each or about $300,000 per year. The $6 million savings presented still does not represent all that is possible from other IR systems.

Table 2. Cost Analysis for Ge Lens

Process	Cost in Dollars/Each*	
	Current Approach	MM&T Approach
Raw Material:		
Germanium Blank($151) less Salvage	82	
Germanium Powder($69)		32
Rough Forming:		
Grinding and Lapping	83	
Hot Forming		41
Finishing:		
Conventional Polishing	248	
Automatic Polish/SPDT		62
Evaluation:	41	41
Tooling	4	26
Total	$453	$202

*Based on Quantity of 1000/month

Section II
Program Progress and Status

A description of the work to be done in each program task and subtask for this MM&T program is included below, along with the progress and status of each subtask and overall program schedule given in Figure 15.

A. TASK 1.0 PROCESS ANALYSIS

Task Objective: This task will establish the materials and processes necessary for the production of more cost-effective Ge lenses typical of those required for IR systems operating in the 8 to 12μm wave length.

1.1 Procure Ge/Refine - Subtask Objective

An established source for the Ge powder and crystal blanks will be compared with material from a new source in this task. If necessary, this material will be purified and regrown to meet the program objectives.

Progress — During this period germanium raw material was ordered from two sources and in several different forms. Three blanks 1.5-inch diameter X 0.5-inch thick of optical grade germanium and 1000 grams of 99.999 percent Ge (first reduction), 100-mesh powder were ordered earlier from Eagle-Pitcher and transferred to this program. A 1000-gram Bridgman grown ingot of Ge doped to 5-20 ohm cm, 12 blanks of Bridgman growth stock, and 12 blanks of replicated (cast) germanium stock were ordered from Exotic Materials. These were received in January and will be used to evaluate the various processing approaches of this task. Half of each group of 12 blanks were ground to 3.0-inch convex by 2.75-inch concave radii for the hot deformation portion of this task.

The 100-mesh powder will be used for our casting-to-shape study, and if it proves to be optically satisfactory, we will consider using this material for other portions of the program.

1.2 Shaping - Subtask Objective

Three hot shaping approaches will be compared with the conventional, rough shaping of flat discs. First, powdered or recycled Ge will be initially melted, refined if necessary, and then cast to shape. In the second approach, slices of refined single crystal Ge will be hot deformed as close to the final shape as possible. The third approach will use cast material that is hot deformed as close to shape as possible.

Progress — The first hot deforming test was made on Eagle-Pitcher 1-1/2-inch diameter curved disc, loaded to 175 psi at a targeted temperature of 850°C. Some edge melting at 940°C occurred, but about 25 percent of the desired deformation did take place. A thermocouple was added to the system and a second 1-1/2-inch diameter curved disc was loaded to 170 psi at 850°C. The hot forming setup used is shown in Figure 16. Note the use of fused quartz and vitreous carbon platens. Very little deformation was obtained with this run; therefore, this part was repressed at 305 psi and 850°C. After the first run, the apparatus

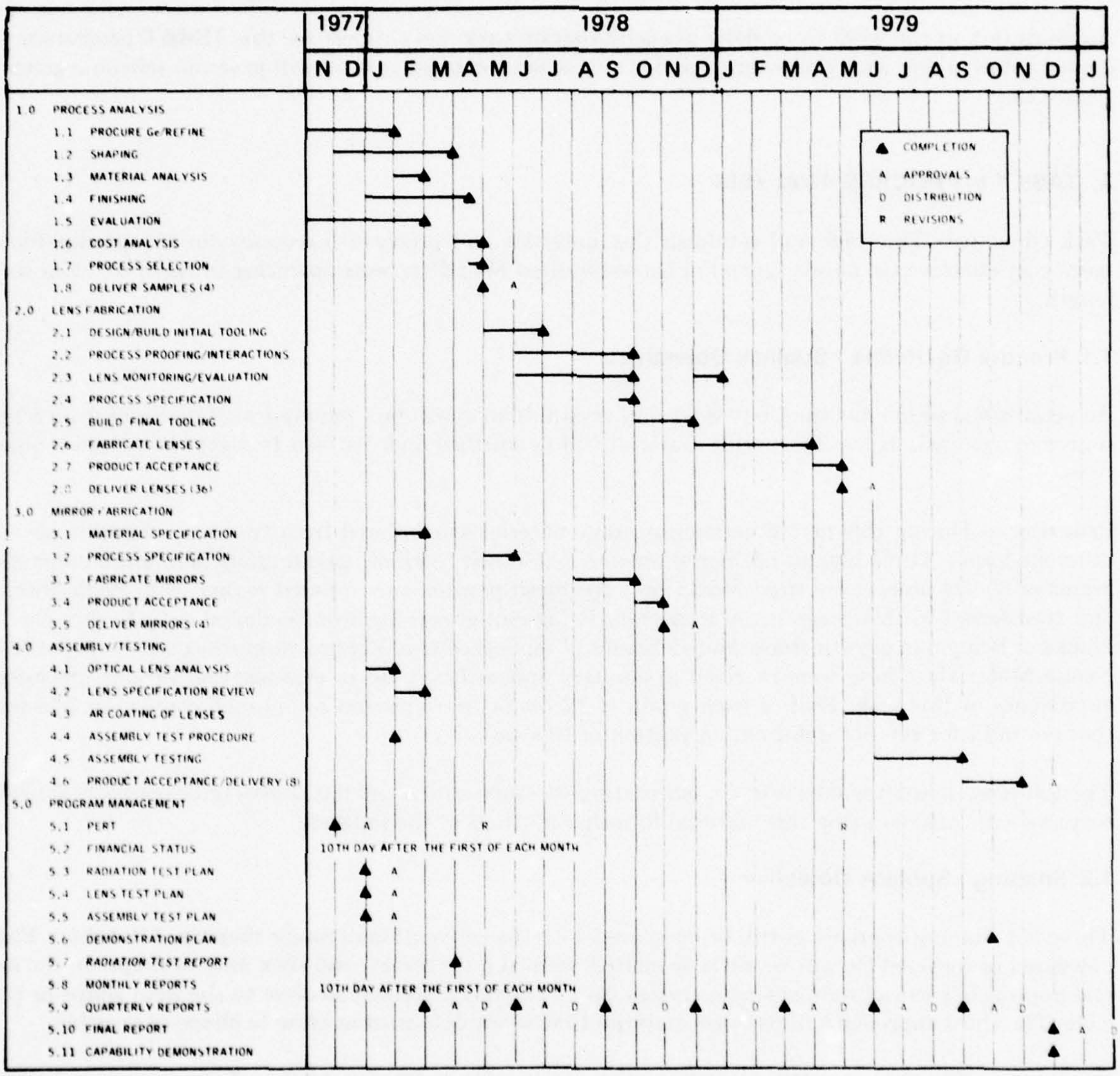

Figure 15. Program Schedule

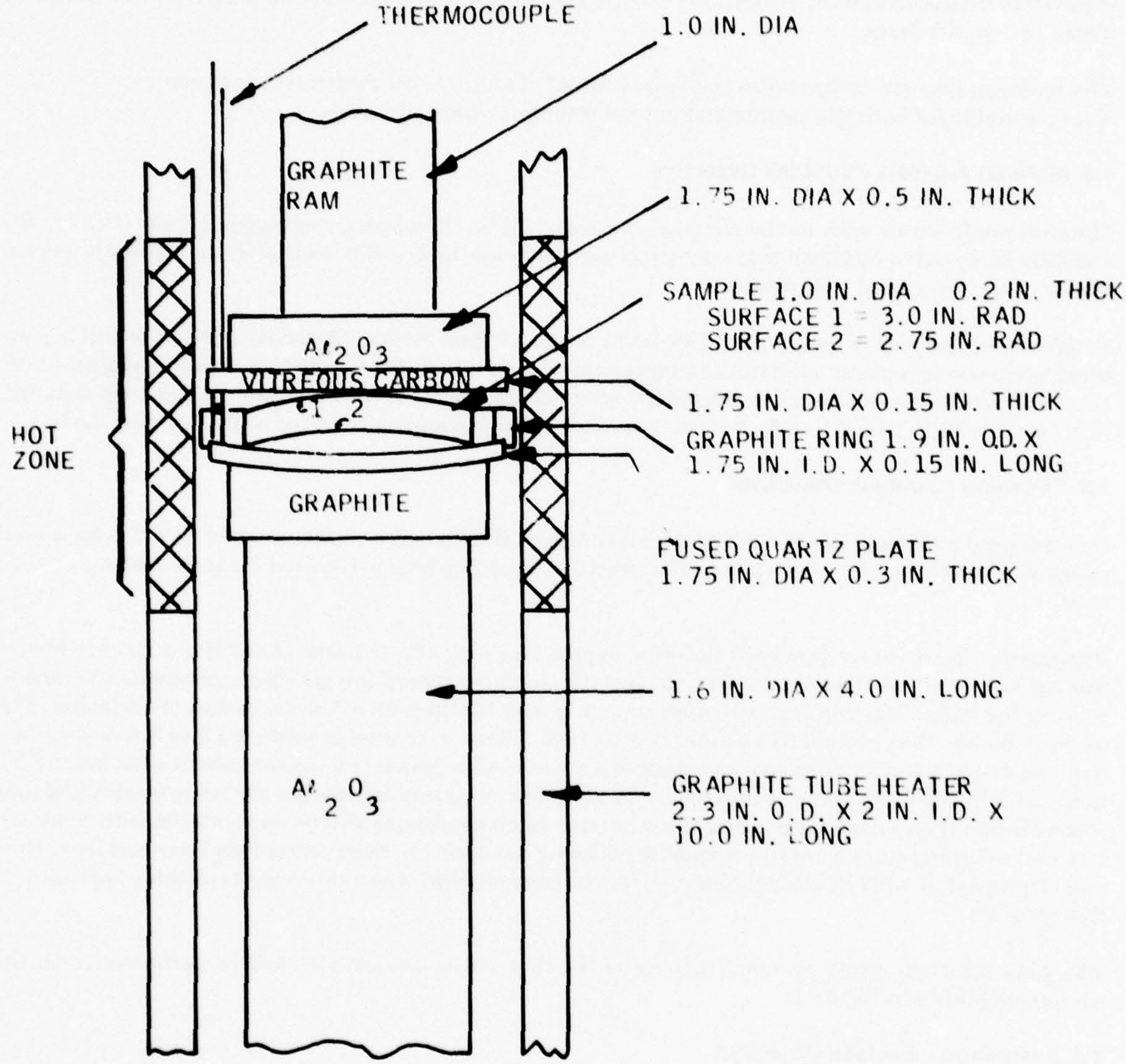

Figure 16. Hot Deforming Equipment

was revised to add alumina thermal insulating pedestals at either ends of the furnace. About 90 percent deformation occurred with the third run. Some peripherial edge chipping took place, but this was related to the wavy surface of the fused quartz pressing plate. The success of this deformation run verifies earlier results obtained with silicon. No sticking occurred between the germanium and polished fused quartz or glassy carbon die faces.

This was also true for carbon when melting occurred. Thus, two die materials have been identified that will be suitable for both the casting and hot deforming-to-shape processes.

1.3 Material Analysis - Subtask Objective

Material produced by each of the shaping processes will be chemically, mechanically, electrically, and optically analyzed to establish that such processing does not have a detrimental influence on the performance of the Ge optical component.

Progress — Samples of each type of material obtained from Exotic Materials and Eagle Pitcher are being prepared for optical, electrical and mechanical evaluation. Discs will be optically polished to obtain IR transmission and optical absorption information, then cut into mechanical test bars that will first be electrically tested by a four-probe approach, then mechanically tested in the bending mode.

1.4 Finishing - Subtask Objective

Conventional polishing, single point diamond turning (SPDT) and a combination of SPDT with a final polish will be evaluated to determine what degree of final finishing is required for each shaping method used.

Progress — Work on conventional finishing approaches was initiated. One of the Eagle Pitcher blanks was cut in half to yield two discs about 0.23-inch thick. Curve generation grinding equipment was used to prepare the initial two thin and two other thick 1/2-inch blanks with a concave radius of 5.6 inches. The second side was then ground to a similar convex radii. These were used in subtask 1.2 to hot deform to a flat disc shape. A conventional polishing approach was used to generate a convex spherical surface with a radius of 3.22 inches. Lapping compounds, oils, laps, and mounting approaches are being established that will maintain their shape during long duration use. Such conditions will be encountered with more automated polishing equipment. A six-spindle polishing machine has been ordered and received from Prismoid Optical that will be installed and used for the conventional, more automated polishing approach on this program.

The work on single point diamond turning of the first set of flat samples will be performed with the equipment shown in Figure 11.

1.5 Evaluation - Subtask Objective

An optical monitoring approach suitable for in-process measurement of the optical figure of a lens will be established. Standard Honeywell lens-testing procedures will be evaluated to establish their suitability for low-cost production.

Progress — Work on a process for optical monitoring has not yet been initiated; however, final testing of lens shapes can be done with the Tropel Interferometer. An interferogram of the 3.22-inch convex radius polished surface (from subtask 1.4) with the Tropel equipment is shown in Figure 17. Such interferograms can be computer analyzed to produce data on the departure from the desired sphericity or asphericity.

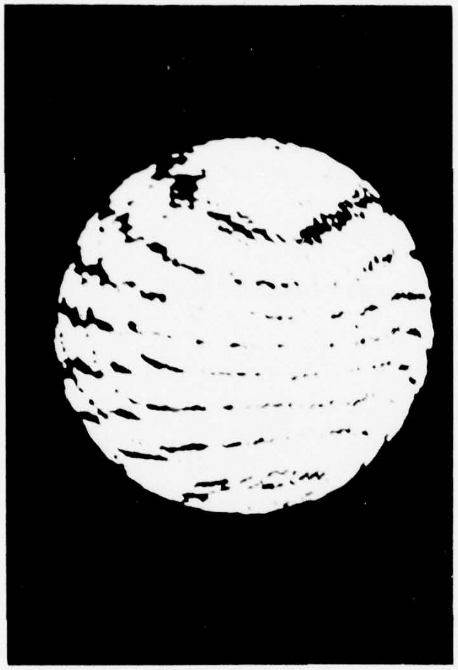

Figure 17. Tropel Interferogram Showing Conformity to a Sphericity of 3.22-Inch Radius

1.6 Cost Analysis - Subtask Objective

A material and process cost analysis of all of the techniques examined will be projected to volume production (1200/month) for each lens type. Inactive.

1.7 Process Selection - Subtask Objective

Based on the performance and cost analysis determined, a first choice process for each lens configuration will be selected and recommended to the contract monitor for his approval. Inactive.

1.8 Deliver Samples (4) - Subtask Objective

A minimum of four samples of the processes examined will be submitted for further customer evaluation. Inactive.

B. 2.0 LENS FABRICATION

Task Objective: This task will implement and verify all of the prototype equipment, tooling, and any new test equipment required to produce and evaluate the IR lenses required for this MM&T program.

No active effort on this task was planned or made during this period.

2.1 Design/Build Initial Tooling - Subtask Objective

The equipment and tooling necessary for both spheric and aspheric lens fabrication will be initially designed, based on SK-AB-114-2 and SK-AB-115-2 lenses, respectively.

2.2 Process Proofing/Interactions - Subtask Objective

Prototype lenses will be fabricated from the initial tooling built. Any tooling modifications and process interactions required to establish the final lens fabrication process will be accomplished in this subtask.

2.3 Lens Monitoring/Evaluation - Subtask Objective

An in-process lens monitoring technique will be established and a lens acceptance test setup will be established.

2.4 Process Specification - Subtask Objective

A tentative process description will be written for each lens type.

2.5 Build Final Tooling - Subtask Objective

All equipment and tooling not previously built will be completed and debugged for the lens fabrication verification part of this task.

2.6 Fabricate Lenses - Subtask Objective

A minimum of 36 uncoated lenses will be fabricated to fulfill the SLIN 0001AB requirement.

2.7 Product Acceptance - Subtask Objective

Each of the lenses produced will be evaluated to determine its conformance to the drawing and paragraphs 3.2-3.4 specification requirements. The data obtained will be documented and submitted for approval.

2.8 Deliver Lenses (36) - Subtask Objective

Customer in-house acceptance of the 36 deliverable uncoated lenses will be obtained in order that these units can be used in Task 4, Assembly Testing.

C. TASK 3.0 MIRROR FABRICATION

Task Objective: Honeywell's single point diamond turning equipment will be used to fabricate the four SK-AB-116-1 mirrors required for this program.

3.1 Material Specification - Subtask Objective

The mirror drawing SK-AB-116-1 will be reviewed with the customer to determine the most cost-effective material and mounting approach to be used in the test assembly for Task 4.

Progress — A meeting was held at Night Vision Laboratory at Fort Belvoir 25 January 1978 with Jim Kelly, David Helm et al. to discuss the mirror drawing requirements on SK-AB-116-1. As indicated in our proposal, we requested that the honeycomb structural material be deleted to allow single point diamond turning to be used for this aspheric mirror. It was agreed that this could be done, and we will submit a revised drawing for this component.

3.2 Process Specification - Subtask Objective

All of the tooling equipment and processes required to build the mirrors will be determined and specified. Inactive.

3.3 Fabricate Mirrors - Subtask Objective

Four mirrors will be fabricated according to the specification in 3.2. Inactive.

3.4 Product Acceptance - Subtask Objective

Each of the mirrors will be evaluated to determine its conformance to drawing SK-AB-116-1. The data obtained will be documented and submitted for approval. Inactive.

3.5 Deliver Mirrors (4) - Subtask Objective

Customer in-house acceptance of the four mirrors built will be obtained in order that these units can be evaluated further in Task 4. Inactive.

D. 4.0 ASSEMBLY/TESTING

Task Objective: The existing FLIR testing facilities will be used to evaluate each lens element individually and collectively in its respective wide field and narrow field objective assembly.

4.1 Optical Lens Analysis - Subtask Objective

A detailed computer optical analysis of each element lens used in each objective assembly will be made to determine the projected OTF performance of each Type A and Type B assembly.

Progress — See 4.2 below.

4.2 Lens Specification Review - Subtask Objective

A specification review based on the optical analysis conducted in 4.1 will be made with the customer to obtain approval for any specification modifications that may be necessary.

Progress — In the 25 January 1978 meeting discussed above, we also reviewed the lens drawing requirements versus the optical assembly performance specifications in MM&T 779845 of Appendix B.

A conflict between the lens drawing requirements and the optical assembly test specifications, originally identified in our proposal, was found by D. Helm to have been caused by an error in the drawings with the exponents for the aspheric surface description. These changes were made and the lenses again computer evaluated for conformance to the OTF optical assembly specification. The new OTF curves are given in Figures 1 and 2 for each assembly. After the exponent changes were made to the lens drawings, the specification for the wide angle afocal assembly was found to be satisfactory; however, the specification for the narrow angle afocal assembly will need a minor correction in the performance curve to allow for manufacturing tolerances and physical locations of several optical apertures. Honeywell was requested to submit a recommended specification change.

4.3 AR Coating of Lenses - Subtask Objective

An antireflective coating meeting the requirements for radiation and MLAR 306 specification (Dwg. SM-C-773691 dated 30 March 1976) will be applied to each lens surface of the 36 lenses made in Task 2.0. Inactive.

4.4 Assembly Test Procedure - Subtask Objective

A test plan for the assembly test will be documented and submitted to the customer for approval. Inactive.

4.5 Assembly Testing - Subtask Objective

One test assembly cell for each of the Type A and Type B objectives will be built and four mirror/lens sets will be evaluated for each type of assembly. Inactive.

4.6 Product Acceptance/Delivery (8) - Subtask Objective

The data obtained for each assembly will be documented and the two test cells and eight mirror/lens sets will be delivered.

E. TASK 5.0 PROGRAM MANAGEMENT

Task Objective: The technical data items and capability demonstration program to be performed throughout the MM&T program will be performed in this task.

5.1 Program Evaluation and Review Technique (PERT) - Subtask Objective

The work breakdown structure defined in this section will be reviewed with the customer and modified as required by any contract negotiations that may influence this structure. A PERT chart will then be submitted with at least 75 elements for the contract monitor's control of this program. Periodic revisions of this chart will be made as required.

Progress — A PERT chart has been prepared, reviewed and revised several times to reflect the extended time required to define the program changes related to the lens and mirror drawings. The final version of this chart will be submitted next quarter.

5.2 Financial Status Reports - Subtask Objective

Submit monthly funds expenditure reports which conform to DI-A-5003B, dated 8 October 1975.

Progress — All monthly cost status reports for each month of the period were submitted prior to the distribution of this quarterly report.

5.3 Radiation Test Plan - Subtask Objective

Submit a radiation test plan in accordance with supplementary information DI-T-1903, dated 15 December 1969.

Progress — A radiation test approach has been established that should be more accurate than the Alpha probe approach recommended in Section F.10.C.3 of the proposal. This approach uses a 1/2-inch diameter measuring area with an event counter (surface barrier detector). The final test plan will be submitted next quarter for approval.

5.4 Lens Test Plan - Subtask Objective

Submit a lens test plan in accordance with DI-T-1906, dated 15 December 1969. Inactive.

5.5 Assembly Test Plan - Subtask Objective

Submit an assembly test plan in accordance with DI-T-1906, dated 15 December 1969. Inactive.

5.6 Demonstration Plan - Subtask Objective

Submit a demonstration test plan in accordance with S-5138, dated 1 October 1967. Inactive.

5.7 Radiation Test Report - Subtask Objective

Submit a radiation test and X-ray diffraction test report to demonstrate Honeywell's capability to measure radiation and chemistry for a controlled set of government standards, as well as routine incoming raw materials and vendor coatings. Inactive.

5.8 Monthly Reports - Subtask Objective

Submit monthly progress reports within 10 days after the end of each month in accordance with DI-S-1800 and addendum No. 2, dated 15 December 1969 and 12 July 1974, respectively.

Progress — All monthly reports have been submitted prior to the distribution of this quarterly report.

5.9 Quarterly Reports - Subtask Objective

Submit quarterly progress reports within 30 days after the end of each quarter in accordance with DI-S-1800, dated 15 December 1969.

Progress — This quarterly report covers the initial period of the program through 1 February 1978. This more extended period was caused by the delay in obtaining resolution of the lens and mirror changes.

5.10 Final Report - Subtask Objective

Submit a final technical report within 30 days after the completion of the technical effort in accordance with DI-S-1800, dated 15 December 1969. Inactive.

5.11 Capability Demonstration - Subtask Objective

Make a capability demonstration to an invited list of no more than 50 representatives of industry and government within 30 days after completion of the final report and approval of the demonstration plan. Inactive.

Section III
Conclusions

The initial materials required for this program have been received and used to demonstrate the feasibility of hot deforming germanium to the desired shape. Initially, the desired shapes are flats, but lens shapes will, of course, be considered next. Spherical surface polishing and evaluation techniques have also been initially established for this program. Several drawing modifications have been made based on a computer analysis technique to yield better aspherical surfaces. These now appear to be suitable to meet the required optical assembly performance.

Section IV
Program for Next Interval

During the next quarter, most of the work on the initial Task I effort on Process Analysis will be completed. At least four optical flat samples for each of the four processes being analyzed in this task will be prepared, optically polished, and optically evaluated.

The final specifications for each lens and mirror to be fabricated in Tasks 2 and 3 will be resolved, along with the optical performance specifications for the Task 4 effort on assembled optical components.

Section V
Publications and Reports

No reports, talks, or publications were made on the work associated with this program during the current quarter.

Section VI
Personnel

During the first quarter of this program the following personnel worked the indicated hours in their areas of responsibility. More detailed background on each professional person follows:

Individual	Responsibility	Hours
W.B. Harrison	Program Manager, Co-Principal Investigator, Lens Fabrication and Evaluation	115
F.E. Johnson	Co-Principal Investigator, Diamond Turned Optical Fabrication Assembly Evaluation	56
I.R. Abel	Optical Design Verification	20
W.T. Boord	AR Coating Design and Fabrication	0
M.E. Curcio	Optical Programming Control	10
G.O. Hendrickson	Germanium Fabrication	90
L.F. Hiltner	Quality Assurance	12
L.W. Luban	Optical Component and Assembly Evaluation	0
T.J. McGran	Single Point Diamond Turning	6
J.E. Starling	Lens Finishing and Evaluation	119
D.F. Marotte	Technician, Lens Finishing	50
M.P.T. Murphy	Technician, Germanium Fabrication	0
M. Sandberg	Technician, Germanium Machining	160

W.B. HARRISON, Senior Principal Ceramic Engineer

Education: BS, Ceramic Engineering, Virginia Polytechnic Institute, 1950.
MS, Ceramic Engineering, Virginia Polytechnic Institute, 1951.

Program Responsibility: Program Manager and Co-Principal Investigator on lens fabrication and evaluation.

Experience: As a Senior Principal Ceramic Engineer, Mr. Harrison is presently program manager of an AFML contract on halide materials processing for high power, infrared laser windows. In this program, large, high strength alkali halide windows for high power CO_2 lasers have been developed by use of three

basic strengthening approaches — recrystallization, solid-solution alloying and the dual process of alloying and recrystallization. Using this approach, KCl-KBr, KCl-RbCl and KCl-$EuCl_2$ alloys with yield strengths greater than 6000 psi have been produced. Mr. Harrison has organized the Ceramic Center's optical measurement capabilities for controlling the optical quality of halide windows.

In his 18 years at Honeywell, Mr. Harrison has also been engaged in development work on the chemistry and processes involved in obtaining submicron particles of such materials as MgO, NiO, TiC and various compounds in the solid-solution series of lead zirconate-lead titanate. Coprecipitation processes based on oxalate techniques, as well as alkoxide techniques, were studied.

Complete fabrication techniques for all types of magnesium oxide products have been developed and placed into commercial production at the Ceramics Center. Among Mr. Harrison's accomplishments was the successful development of transparent MgO material, as well as controlled high porosity formulations. Extensive product development activities were carried out in the use of high purity MgO materials. Among these were property studies made on corrosion resistance and strength at temperatures to 4500°F and infrared transmission characteristics as a function of microstructural variations such as grain size, porosity, and purity.

Publications: Mr. Harrison's publications include the following:

- "Influence of Surface Conditions on the Strength of Polycrystalling MgO," J. Am. Ceramic Society, Volume 47, Number 11, page 573 (1964).
- "Mechanical Behavior of *Polycrystalline Ceramics,*" *Final Report*, AROD ContractDA-11-022-ORD-3441, April 1965.
- "Unconventional Processes for Fabricating Ceramics," Final Report, Sandia Contract 58-4450, November 1969.
- "Halide Materials Processing for High-Power Infrared Laser Windows," AFCRL-TR-73-0372(11) Special Reports, No. 162, 19 June 1973, Conference on High Power Infrared Laser Window Materials, p. 391, October 1972.
- "Mechanical and Optical Properties of Recrystallized Alkali Halide Alloys," AFCRL-TR-74-0085(11) Special Reports, No. 174, 14 February 1974 Third Conference on High Power Infrared Laser Window Materials, p. 615, November 1973.
- "The Growth, Characterization and Recrystallization of Alkali Halide Alloyed and Doped KCl," Proced. 4th Conference on Infrared Laser Window Materials, p. 599, January 1975.

FLOYD E. JOHNSON, Senior Principal Engineer

Education: BSME, Purdue University, 1952.
Graduate studies, Brooklyn Polytechnic Institute and Northeastern University.

Program Responsiblity: Co-Principal Investigator on diamond turning lenses and mirrors and assembly evaluation.

Experience: Mr. Johnson is currently Program Manager on the Manufacturing Methods and Technology contract for FLIR Cost Reduction sponsored by the Air Force Materials Laboratory, WPAFB, OH. The program's objective is to prove acquisition and life cycle cost saving feasibility of advanced materials and techniques applied primarily to the Air Force Common Modular FLIR AN/AAQ-9 (XA-2). Program results will also apply to other FLIRs, as well as to other thermal imaging systems. One example of evaluations being conducted is the feasibility of using hot-forged salt lenses to replace expensive infrared transmitting materials.

As a staff engineer, Mr. Johnson provided key technical contributions during development responsibility for components critical to thermal imaging systems: cryogenic coolers, vacuum dewars, ultra high speed ball bearings, high resolution multibeam CRTs, lenses, mirrors, coatings, etc. Mr. Johnson was previously Project Engineer on the AN/AAD-5 Infrared Reconnaissance Set during its highly successful development for the Air Force. Other project engineering assignments at Honeywell Radiation Center included: the ALERTS project, which built a scan converter-driven display for a forward looking laser line scanner and an IR/Optics module for the Redeye Trainer.

Prior to joining Honeywell in 1964, Mr. Johnson was employed at two small business concerns that developed and marketed precision photo/optical instrumentation. He was Vice President of Sales for Vertex Development Corporation and Director of Engineering for Photomechanisms, Inc.

IRVING R. ABEL, Senior Principal Engineer

Education: BS, Optics, University of Rochester, 1944.
MS, Physics Syracuse University, 1948.
Graduate courses in Physics (fulfillment PhD course requirements), New York University.

Program Responsibility: Optical design verification.

Experience: As a Senior Principal Engineer, Mr. Abel is leading the optical design activity for FLIR systems.

Mr. Abel has 27 years of experience in the field of Optical Design, Optical Engineering, and Radiation Physics at Honeywell, Bausch & Lomb Optical Co., Farrand Optical Co., Norden Division of United Aircraft and Baird-Atomic, Inc., including telescopic, periscopic, and viewing systems, using moderate and large-scale digital computers. Designs include airborne and spaceborne systems.

Recently, Mr. Abel invented the optical system for the Skylab S-192 Multispectral Scanner and has led the optical design activity for FLIR systems.

Patents: Mr. Abel's work includes the following patents:

- High Aperture Wide Field Varifocal Scanning System, Patent No. 3,519,325.
- Collimated Viewing System, Patent No. 3,446,916.
- Infrared Imaging Apparatus, Patent No. 3,728,545.
- Optical Instruments, Patent No. 3,782,835.
- Wide Field Reflective Optical Apparatus, Patent No. 3,811,749.

W. TIMOTHY BOORD, Principal Research Scientist

Education: BS, Physics, Case Institute of Technology, 1966.
MS, Physics, Case Western Reserve University, 1969.
PhD, Physics, Case Western Reserve University, 1973.

Program Responsibility: AR Coatings design and fabrication.

Experience: Dr. Boord joined Honeywell in September 1973. He has been the principal investigator on three programs dealing with optical coatings on transparencies. One of the programs involved research on the application of semiconducting films for eye protection from IR lasers. The other two programs concern the development of antistatic coatings and heat- and abrasion-resistant coatings for aircraft transparencies. He has also been involved in programs to develop protective antireflection coatings for high energy laser windows.

His graduate research was in solid-state physics and modern optics. His thesis concerned the design and development of an optical isolator for high powered carbon dioxide lasers. The isolator used the free electron Faraday rotation in the semiconductors. His graduate work also involved studying defects in semiconductors and alkali halides using the electron nuclear double resonance technique, and the growth of lead tin telluride crystals by the vapor transport method.

Publications:

- W.T. Boord, Y.H. Pao, F.W. Phelps, Jr., and P.C. Claspy, "Far-Infrared Radiation Isolator," IEEE J. Quantum Electron, Vol. QE-10, pp. 273-279, February 1974.

- W.T. Boord, Y.H. Pao, F.W. Phelps, Jr., and P.C. Claspy, "Far-Infrared Radiation Isolator," presented at the IEEE/OSA Conference on Laser Engineering and Applications, Washington, D.C., May 1973.

- W.T. Boord, A.Y.B. Mar, W. Harrison and J. Sterling, "The Development of Antireflective Thin Films for Polycrystalline Alkali Halide Laser Window Materials," Proceedings of the Fifth Annual Conference on Infrared Laser Window Materials, 1976.

- Also report AFML-TR-76-160 by the same title.

G.O. HENDRICKSON, Senior Materials Engineer

Education: BS, Metallurgical Engineering, Michigan Technological University, 1957.

Program Responsibility: Material Purification and Lens Shaping.

Experience: Mr. Hendrickson joined the development engineering staff of the Ceramics Center in June 1972 and is currently investigating machining, hot forging and thermal processing of halide crystals for high power laser windows (AFML Contract No. F33615-72-C-2019).

He transferred from the Honeywell Aerospace Division where for 12 years in the Materials and Process (M&P) Engineering Section he worked on the application of ceramic-to-metal, glass-to-metal and anodic bonding to aerospace hardware. During this time, he was assigned to a consulting specialty in both nondestructive testing and experimental stress analysis.

Included in Mr. Hendrickson's prior assignments as a materials and process applications engineer were: (1) design and production engineering support on numerous aerospace programs; (2) specialist in module interconnect welding fabrication; (3) establishment of a failure analysis laboratory and directing mechanical and metallurgical analysis; and (4) specialist in experimental stress analysis and electronic module welding process development.

Before joining Honeywell, Mr. Hendrickson worked for Marquette Manufacturing Co., as a laboratory development metallurgist with primary responsibility for developing flux coatings for welding electrodes. He assisted in training sales personnel and resolving customer technical problems.

Publications: Mr. Hendrickson's publications include:

- "Halide Materials Processing for High-Power Infrared Laser Windows," AFCRL-TR-73-0372(11) Special Reports, No. 162, 19 June 1973, Conference on High Power Infrared Laser Window Materials, p. 391, October 1972.

- "Mechanical and Optical Properties of Recrystallized Alkali Halide Alloys," AFCRL-TR-74-0085(11) Special Reports, No. 174, 14 February 1974, Third Conference on High Power Infrared Laser Window Materials, p. 615, November 1973.

LEON F. HILTNER, Senior Quality Engineer

Education: BS, Mechanical Engineering, University of Minnesota, 1960.

Program Responsibility: Quality Assurance

Experience: Mr. Hiltner is currently serving as the Lead Quality Engineer at the Honeywell Ceramic Center. In his present assignment, he directly supervises Quality Assurance engineers and technicians on both development and production programs.

Mr. Hiltner's prime specialty is Statistical Quality Assurance. He is certified by the American Society for Quality Control (ASQC).

Mr. Hiltner has worked in the Honeywell Quality Department for the past 15 years. His most recent previous assignment involved total quality program responsibilities for Sandia/AEC Inertial Switch development and fabrication. Among other assignments, Mr. Hiltner served on the Quality Director's staff. During this time, he developed and taught a 60-hour, in-plant training program in Industrial Statistics, prepared divisional operating procedures, and was liaison between the Quality Department and the Data Systems Planning group.

MICHAEL E. CURCIO, Senior Development Engineer

Education: BS, Physics, Manhattan College, 1968.
Graduate studies: 34 quarter hours toward MSEE, Northeastern University.
15 credit hours in Physics, Syracuse University.

Program Responsibility: Control of SPDT lens/mirror fabrication.

Experience: As a Senior Development Engineer, Mr. Curcio is the project engineer for the design and implementation phases of the N/C diamond turning for the IR Optics Program, and for the vacuum/cryogenic Low-Background Calibration Facility for IR radiometers.

In his four years of experience at Honeywell, Mr. Curcio has designed and implemented the sensor off-axis rejection and mirror-low-scatter measurement facilities; implemented an IR heterodyne detector test facility; completed calibration, alignment and systems testing of navigational star trackers for the Viking Orbiter '75 and Application Technology Satellite (ATS) programs; and has full technical responsibility for the ATS baffle evaluation. Prior to joining Honeywell, Mr. Curcio was a project engineer in electro-optical methods for reconnaissance exploitation with the Department of the Air Force at the Rome Air Development Center (RADC).

Publications: Mr. Curcio published the following:

- "Evaluation of Low-Scatter Technology for Aspheric Metal Mirrors," SPIE Vol. 65 (1975) Metal Optics.

VLADIMIR W. LUBAN, Senior Principal Development Engineer.

Education: MSEE (equivalent) studies in Mathematics and Physics at Wagner College, and Electrical Engineering at Cooper Union School of Engineering.

Program Responsibility: Lens/mirror evaluation.

Experience: Mr. Luban is a Senior Principal Development Engineer who directs an optical test group of 10 engineers and five data reduction personnel. He has responsibilities in opto-mechanical design and optical testing, mirror and mount design for a number of high performance systems, including ELS, ELMS, HEAO-B, AAD-5 and HIRIS; directing team which developed alignment procedures and ran proving laboratory tests on the highly advanced Type 18 submarine periscope; releasing "hold" order on major program by redesigning flotation support, originally costing $50,000, of 60-inch diameter flat mirror, which held flatness to 1/8λ peak-to-peak, at a fixed cost of $3,000 including materials and labor; assembling and aligning a 50-inch diameter Cassegrainian collimator; designing and building two types of stable frequency helium neon lasers; working with Dr. Roland Shack on developing equipment for measuring Modulation Transfer Function of high resolution photographic systems; and Optical Engineer responsible for performance on four — $1,500,000 ROTI MKII tracking cameras, one of which took the first American photograph of Sputnik I.

Mr. Luban is a Senior Principal Development Engineer whose 22 years of experience at Honeywell, Itek, Perkin-Elmer and American Bosh Arms Corp. include directing engineering groups, research and instrument development, system design and alignment, and testing of state-of-the-art high resolution photographic systems. These activities were coordinated with other disciplines, such as electronics, high vacuum, high altitude problems, cryogenics, etc. Specifically, the experience includes: design of production optical test station for test of AAD-5 components; design and build of a LUPI (Laser Unequal Path Interferometer), which is being used as a basic optical alignment and test instrument both at HRC and at some of our optical vendors; conceiving and implementing a technique based on white light interferometry for measuring equality of multiple arm lengths to accuracies of 6 microinches.

THOMAS J. McGRAN, Manager of Manufacturing

Program Responsibility: Single point diamond turning.

Experience: As Manager of Manufacturing, Mr. McGran is presently responsible for electronic packaging engineering, design drafting, material control, manufacturing engineering, model shop and fabrication and assembly operations. Recent experience includes integration and direction of these activities on the ICECAP/HIRIS program, as well as AAD-5 Mapping and S192 13-Band Scanner systems.

Mr. McGran's 17 years of previous manufacturing experience at Honeywell includes: management of manufacturing operations on the AOSO FINE SUN SENSOR program, which included material control, model shop, production engineering and fabrication groups; production manager on IRATE, and supervisor of manufacturing, assembly and planning on the Trump Radiometer.

JOSEPH E. STARLING, Development Engineer.

Education: BS, Ceramic Engineering, University of Missouri-Rolla, 1967.
MS, Ceramic Engineering, University of Missouri, Rolla, 1971.

Program Responsibility: Lens/finishing and evaluation.

Experience: Mr. Starling is assigned to the alkali halide infrared laser window program. He is responsible for the hot forging recrystallization studies on such halides as NcCl, KCl, KBr and their alloys. Included in his tasks are microstructural analysis, finishing, optical polishing and mechanical strength behavior of these as well as other ceramic materials.

At the University of Missouri-Rolla, he was a PPG Fellow. His graduate study included work on stress-gradient biased diffusion of alkali ions in glasses. He was previously employed as an engineer in the R&D department of Chicago Vitreous Corp., where his work included thermally insulating enamels and enamels with specific electrical properties.

Professional Affiliations: Mr. Starling is a member of the American Ceramic Society, Keramos (Ceramic Engineering Professional Fraternity), and Tau Beta Pi.

Publications: Mr. Starling's publications include:

- "Halide Materials Processing for High-Power Infrared Laser Windows," AFCRL-TR-73-0372(11) Special Reports, No. 162, 19 June 1973, Conference on High Power Infrared Laser Window Materials, p. 391, October 1972.
- "Mechanical and Optical Properties of Recrystallized Alkali Halide Alloys," AFCRL-TR-74-0085(11) Special Reports, No. 174, 14 February 1974, Third Conference on High Power Infrared Laser Window Materials,p. 615, November 1973.

References

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11. G.W. Groves and A. Kelly, Phil. Mag. 8 (1963), p. 877.
12. M.F. Ashby, Acta. Met. 20 (1972), p. 887.
13. A.G. Evans and T.G. Langon, Prog. Mat. Sci. 21 (1976), p. 171.

Glossary

Afocal — An optical system whose object and image point are at infinity.

Anti-reflective (AR) Coatings — A single or multilayer coating applied to a surface or surfaces of a substrate to decrease the reflectance of the surface and increase the transmission of the substrate over a specified wavelength range.

Casting — A method by which a molten material is formed, solidified, and then cooled in a confining die or mold.

Diffusional Flow — The spontaneous movement of atoms to an extent sufficient to cause mass flow of material.

Dislocation Glide — The slip or movement of atoms along planes through dislocations in bulk material.

Dislocations — Defects in the atomic lattice of a crystal represented by the presence of excess atoms or absence of atoms in the normal perfect atomic structure of material.

Dispersion — The process by which rays of light of different wavelength are deviated angularly by different amounts as with prisms and diffraction gratings. Also applied to other phenomena that cause the index of refraction and other optical properties of a medium to vary with wavelength.

Form-to-Shape — A forming process that converts an irregular shape material into a predetermined final shape as defined by a die or mold cavity.

Homologous Temperature — The relationship (ratio) between the working temperature of a material and its melting point, both in degrees absolute.

Hot Deforming — The deforming of a material above its recrystallization temperature which is sufficient to cause bending and distortion of that material into a permanent new shape.

Imager — A single or multiple set of optical elements that form an image by collecting a bundle of light rays diverging from an object point and transforming it into a bundle of rays converging toward another point.

Infrared — The electromagnetic radiation beyond the red end of the visible spectrum (0.768 to 40μm). Heat is radiated in the infrared region. The FLIR ranges of interest are 3 to 5μm and 8 to 14μm.

Interference — A term used to denote the additive process, whereby the amplitudes of two or more overlapping waves are systematically attenuated and reinforced.

Interferometer — An instrument employing the interference of light waves for purposes of measurement, such as the accuracy of optical surfaces by means of Newton's rings, the measurement of optical paths, and linear and angular displacements.

Modulation — A measure of the variation of illuminance across an image of a sine wave object. Defined as $M = (I_{max} - I_{min})/(I_{max} + I_{min})$ where I_{max} and I_{min} are the maximum and minimum illuminance in the image.

Modulation Transfer Function (MTF) — The function describing the modulation intensity of the image of a sinusoidal object with increasing frequency. It describes the results obtained on passing through an optical system. Also called "sine wave response" and "contrast transfer function."

Optical Transfer Function (OTF) — The function describing modulation and spatial phase shift of the image of a sinusoidal object with frequency as the independent variable as a result of passing through an optical train.

Sag — Abbreviation for *sagitta*, the height of a curve measured from the chord (as applied to optics).

Single Point Diamond Turning (SPDT) — A relative new turning technique which uses precision spindles and movements (usually air bearing movements), a high speed single point diamond turning tool that can be moved in microinch stages. This technique has been shown to be especially useful for turning metal mirrors as well as other optical components.

Special Phase Shift — The displacement of the image of a sine wave object from its ideal position. Usually measured in degrees, with 360 degrees assigned to a full cycle of the image.

Thermal Imaging — A representation of an object's thermal profile by means of its IR light rays.

Appendix A
Drawing Requirements

SM-C-772326 SM-C-804148 SM-C-773691
SM-A-774953 SK-AB-108-1 SK-AB-108-2
SK-AB-114, -1, -2 SK-AB-115, -1, -2 SK-AB-116, -1, -2

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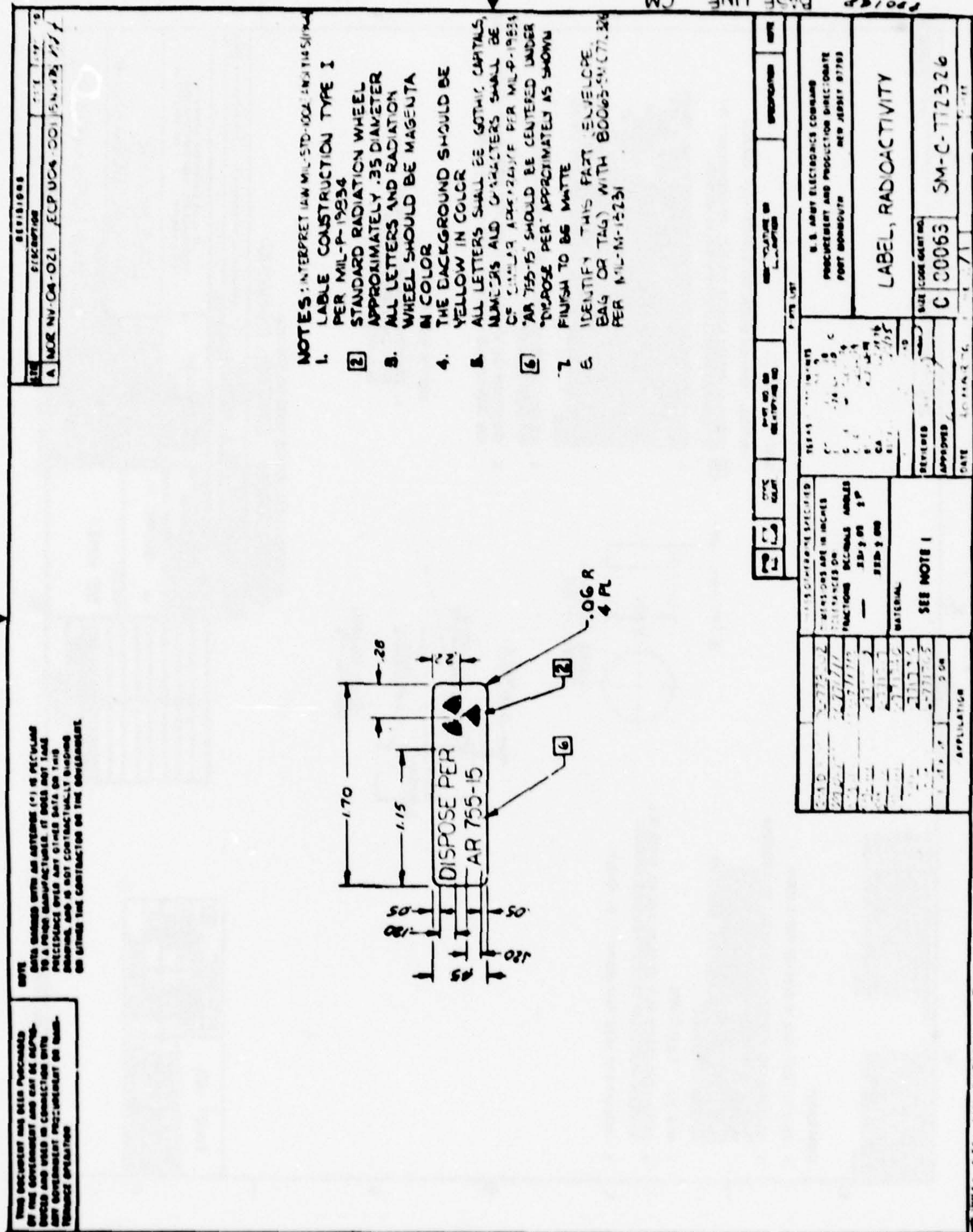

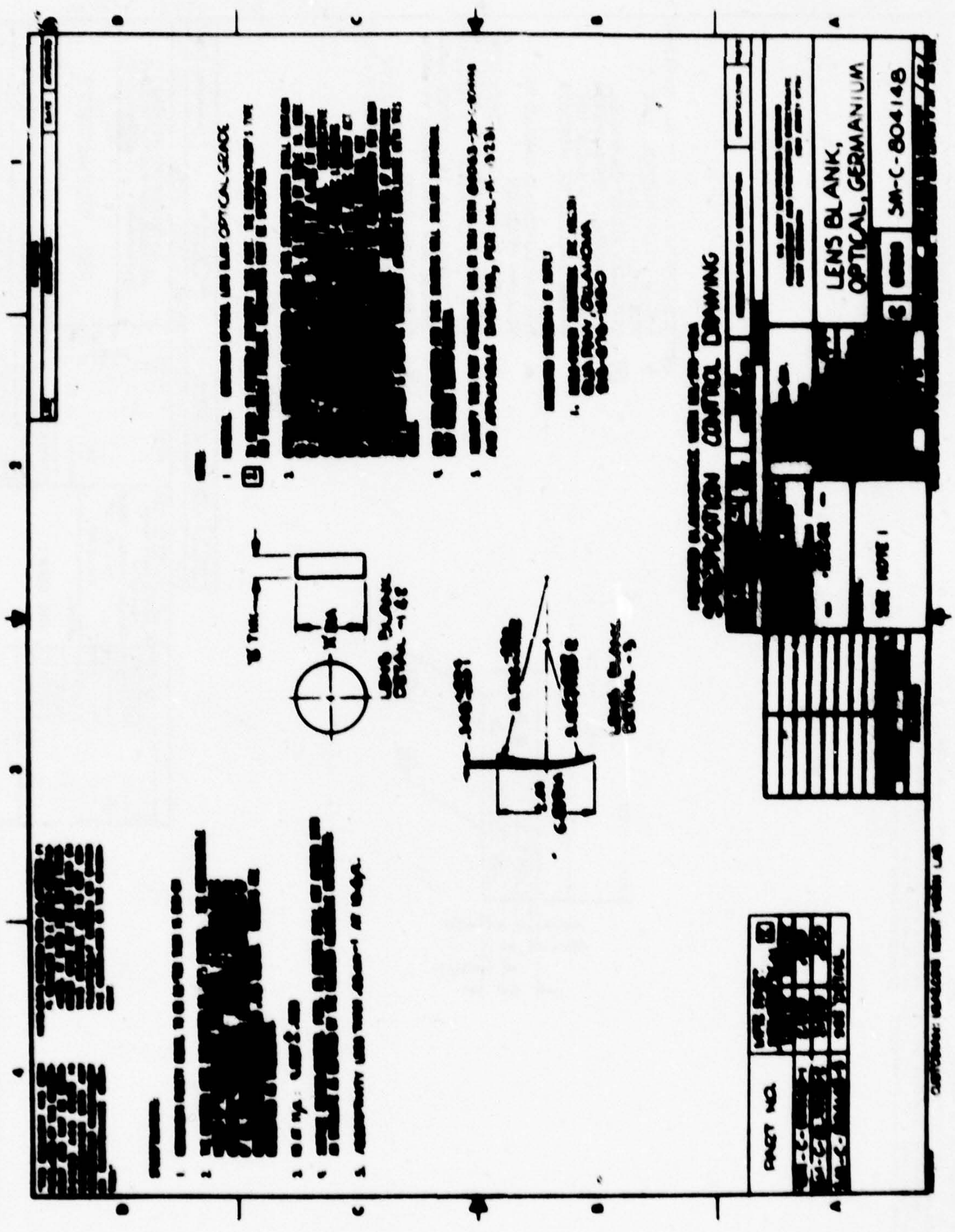
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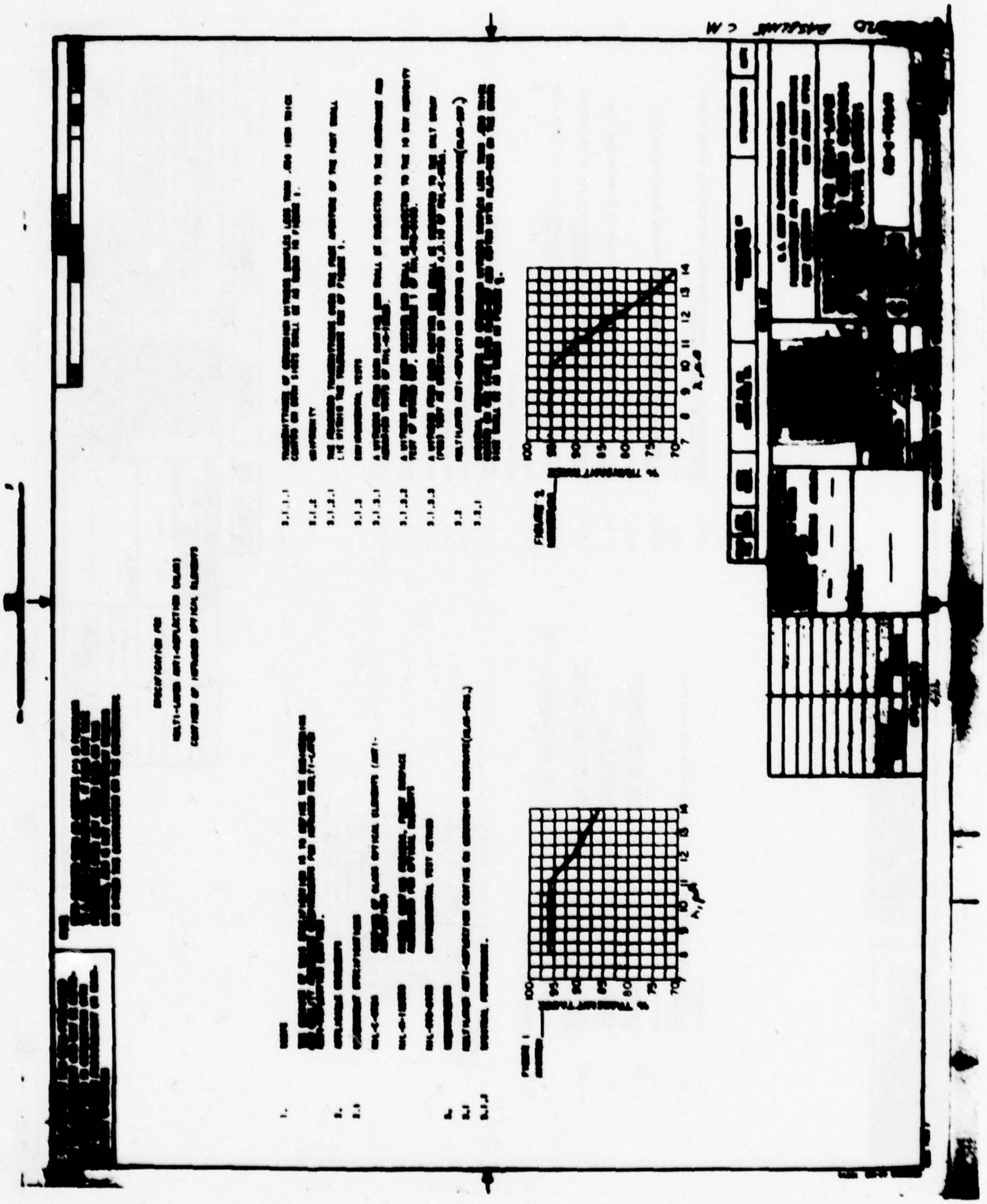

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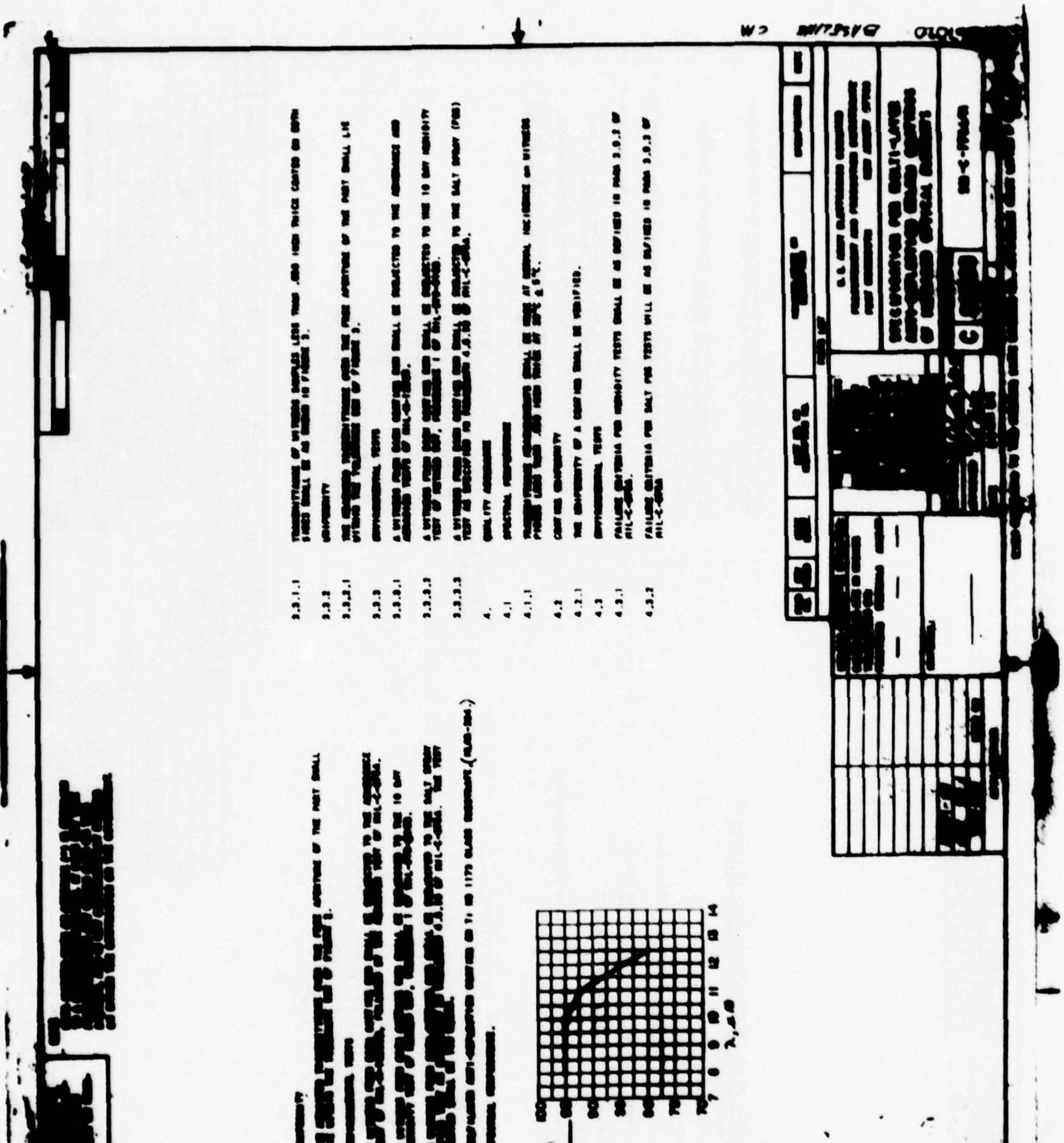

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APPLICATION	
NEXT ASSY	USED ON
SM-D-772005	DL-771711

REVISIONS			
LTR	DESCRIPTION	DATE	APPROVED

ACCEPTANCE TEST PROCEDURE

FOR

AFOCAL/COVER

USAECOM DRAWING SU-94/TAS-4

THIS DOCUMENT HAS BEEN PURCHASED BY THE GOVERNMENT AND MAY BE REPRODUCED AND USED IN CONNECTION WITH ANY GOVERNMENT PROCUREMENT OR MAINTENANCE OPERATION

NOTE
DATA MARKED BY AN ASTERISK (*) ARE FOR INFORMATION ONLY. CONTRACTOR MAY, AT HIS OPTION, DEVIATE FROM THESE DETAILS

REV STATUS OF SHEETS

TEXAS INSTRUMENTS INCORPORATED

DAA[illegible]-74-C[illegible]

U.S. ARMY ELECTRONICS COMMAND
PROCUREMENT AND PRODUCTION DIRECTORATE
FORT MONMOUTH NEW JERSEY 07703

ACCEPTANCE TEST PROCEDURE,
AFOCAL/COVER ASSEMBLY

ELECTRONICS COMMAND
REVIEWED
APPROVED
DATE

NEXT ASSY — USED ON
APPLICATION

SIZE	CODE IDENT NO.	DRAWING NO.
A	80063	SM-A-774953

TABLE OF CONTENTS

SIZE	CODE IDENT NO	DRAWING NO
A	80063	SM-A-774953
SCALE	REV	SHEET 2

D DWG NO ________

1. TABLE OF TESTS

TESTS	PARAGRAPH NO.
Test Equipment Certification	3.1
Afocal/Cover Assembly Drawing Compliance	4.2.1
Field of View Change	4.2.2.2
Focus Operation	4.2.2.3
Modulation Transfer Function	4.3.1

SIZE	CODE IDENT NO	DRAWING NO
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SCALE	REV	SHEET 3

2. APPLICABLE DOCUMENTS

2.1 The following documents are part of this test procedure to the extent specified herein. The most recent issue shall be used unless otherwise specified. If any document should conflict with this procedure, this procedure shall take precedence.

Drawings	Description
USAECOM SM-D-772005-1	Afocal/Cover Assembly

Specifications

USAECOM B2-2301020102	Development Specification, Afocal/Cover Assembly, AN/TAS-4
B2-2301020105	Development Specification, Imager, Optical, Infrared AN/TAS-4

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SCALE	REV	SHEET 4

3. DESCRIPTION OF TEST APPARATUS

3.1 The following instrumentation or equivalent is required for the performance tests listed herein. Verify that test equipment certification is current (Check).

Equipment	Description
Infrared Source	Infrared Industries Model 463
Chopper	Infrared Industries Model 827/828, Blade #1
Collimator	174 inch focal length, off axis, mirror diameter 12", resolution .02 milliradian, useable in the applicable spectral range.
Bandpass Filter	50% transmission points at 7.6 and 11.6 microns
Imaging Lens	Per Specification B1-2301020100
Variable Slit	Hilger Model F1497
Detector	KBr window, Thermopile, Charles M. Reeder and Company Model NSL-68
Edge Translating Device	Tropel Model Miniscan 2100
Amplifier	Ithaco Phase Lock Amplifier Model 353
Optical Bench	Beck Ealing Model 23-0714

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DWG NO ______

3.2 ABBREVIATIONS

3.2.1 Abbreviation	Meaning
UUT	Unit Under Test
MTF	Modulation Transfer Function
AFOCAL	Afocal/Cover Assembly
IMAGING LENS	Imager, Optical, Infrared, AN/TAS-4
WFOV	Wide Field of View
NFOV	Narrow Field of View
lp/mm	Line Pairs per Millimeter

SIZE	CODE IDENT NO	DRAWING NO
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4. TEST PROCEDURES

4.1 Recording Data

4.1.1 All data required during performance of the Acceptance Test shall be recorded on the Acceptance Test Data Sheet. Should the UUT fail any test requirement, the failed parameter shall be clearly identified. Any required data which is produced on a separate chart, graph or table, and any informational comment required for their understanding shall be attached to and become part of the Acceptance Test Data Sheet. Such attachments shall clearly indicate the related Acceptance Test Procedure paragraph. The most recent issue of this Acceptance Test Procedure shall be used.

4.2 Visual Inspection

4.2.1 The UUT shall be examined to verify that all parts materials, processes, subassemblies, and assembly techniques are in accordance with USAECOM drawing SM-D-772005 (Check). Record the UUT MSN (Record).

4.2.2 Functional Test, Field of View Change and Focusing Adjustment.

4.2.2.1 Rest the Afocal on a steady, level surface. Cushioning may be added to protect the surface finish.

4.2.2.2 While steadying the unit with one hand, grasp the field of view shange lever with the free hand. Visually confirm the NFOV position of the switch places the NFOV lens in the optical axis of the unit. Likewise confirm operation of the WFOV position of the lever positions the WFOV lens and baffle in the optical axis. (Check).

SIZE	CODE IDENT NO	DRAWING NO
A	80063	SM-A-774953
SCALE	REV	SHEET 7

4.2.2.3 Continue with the Afocal/Cover Assembly positioned as in 4.2.1.2. Grasp the focus control and rotate it from one extreme to the other extreme while visually confirming motion of the traveling lens carriage. (Check)

4.3 Optical Inspection

4.3.1 Modulation Transfer Function (MTF)

4.3.1.1 Assemble the apparatus as described in Figure 1. Alternatively, any layout may be used which places the elements of the required equipment at their proper optical locations. The test will be performed at infinite conjugates.

4.3.1.2 Operate the infrared source at approximately 1000 degrees centigrade. Set the chopper in motion to interrupt the source at approximatelv 40 Hertz. Install the variable slit at the collimating optics focal point. Obtain a focused image of the slit at the knife edge on the optical axis of the imaging lens.

4.3.1.3 Adjust the imaging lens for best focus. Translate the knife edge across the slit image. Record the detector output versus the knife edge position (Record). Compute the on-axis modulation transfer function (MTF) of the imaging lens between 0 and 15 line pairs per millimeter, either in discrete steps or continuously (Record).

4.3.1.4 Repeat 4.3.1.3, except that the folding mirror and detector must now be repositioned to measure and compute the off-axis modulation transfer function on both sides of center at 1/2 the azimuth field of view (Record). Reposition all components on the optical axis.

4.3.1.5 Install the Afocal/Cover Assembly in the optical axis. See Figure 1. Place the Afocal/Cover Assembly in the WFOV position. Attach the imaging lens to the rear of the assembly. See Figure 1. Focus the afocal for the best image at the imaging lens focal plane. Do not adjust the imaging lens focus.

4.3.1.6 Repeat 4.3.1.3 through 4.3.1.4, except do not adjust the imaging lens focus. The computed modulation transfer function will be the cascaded MTF of the afocal and imaging lenses. (Record). Repeat with the afocal in the NFOV position. (Record).

SIZE	CODE IDENT NO	DRAWING NO
A	80063	SM-A-774953

D DWG NO ____

SCALE	REV	SHEET 9

5. FIGURES

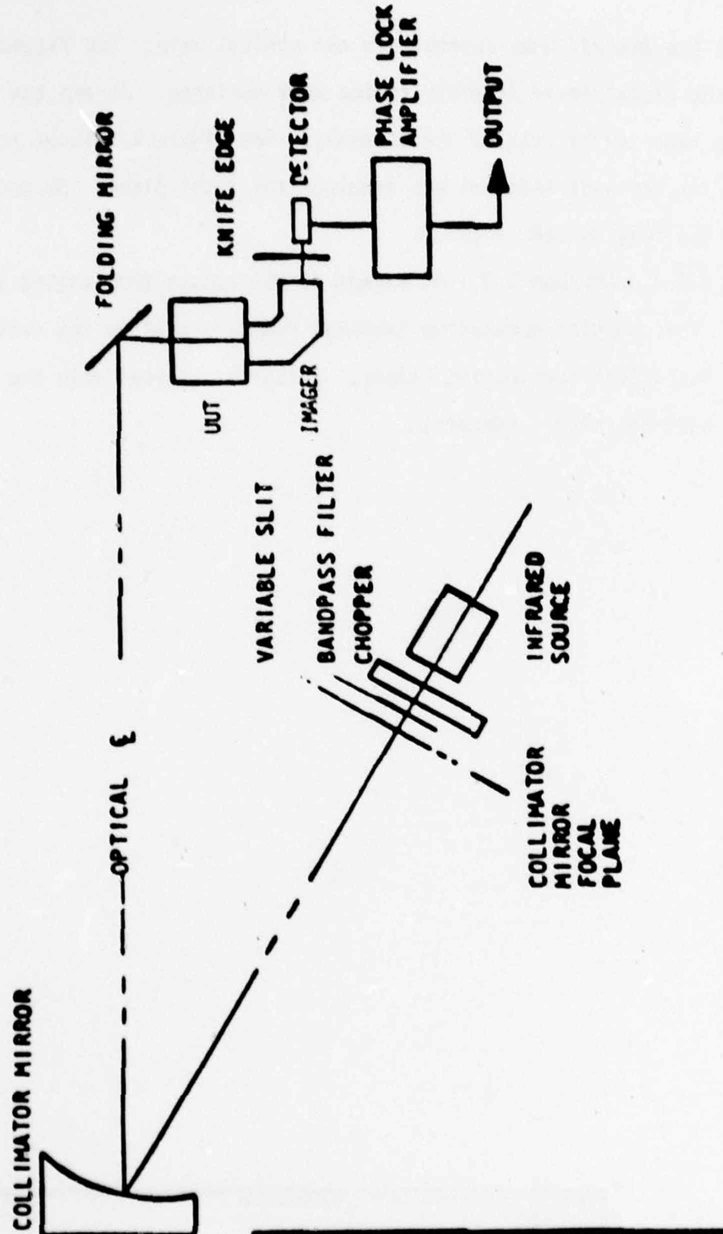


FIGURE 1 TEST LAYOUT

SIZE	CODE IDENT NO	DRAWING NO
A	80063	SM-A-774953

SCALE	REV	SHEET 10

6. ACCEPTANCE TEST DATA SHEET

ACCEPTANCE TEST DATA SHEET

FOR

AFOCAL/COVER

USAECOM DRAWING SU-94/TAS-4

SIZE	CODE IDENT NO	DRAWING NO
A	80063	SM-A-774953
SCALE	REV	SHEET 11

DWG NO

6. ACCEPTANCE TEST DATA SHEET

6.1 The following paragraphs are numbered to correspond with their paragraphs in the Acceptance Test Procedure.

4.2.1 Assembly in accordance with SM-D-772006-1. ________ (Check)

UUT MSN ________ (Record)

4.2.2.2 NFOV lens positioned with engagement of FOV switching lever at NFOV position. ________ (Check)

4.2.2.3 Carriage motion observed when afocal focus is varied. ________ (Check)

4.3.1.3 MTF between 0 and 15 line pairs per millimeter. (Record, or attach record)

Line pairs/mm	MTF	Line pairs/mm	MTF
0	______	8	______
1	______	9	______
2	______	10	______
3	______	11	______
4	______	12	______
5	______	13	______
6	______	14	______
7	______	15	______

4.3.1.4 Off-axis MTF, (Record, or attach record)

LEFT		RIGHT	
Line pairs/mm	MTF	Line pairs/mm	MTF
0	______	0	______
1	______	1	______
2	______	2	______
3	______	3	______
4	______	4	______
5	______	5	______
6	______	6	______

SIZE	CODE IDENT NO	DRAWING NO
A	80063	SM-A-774953

DWG NO ______	SCALE	REV	SHEET 12

4.3.1.4 Continued:

LEFT		RIGHT	
Line pairs/mm	MTF	Line pairs/mm	MTF
7	______	7	______
8	______	8	______
9	______	9	______
10	______	10	______
11	______	11	______
12	______	12	______
13	______	13	______
14	______	14	______
15	______	15	______

4.3.1.6 Afocal MTF. Record value equal to (MTF Read). Corresponding MTF from 4.3.1.3) (Record). For Test Limits, See specification B2-2301020102, Figure 1.

ON AXIS		LEFT		RIGHT	
Line pairs/mm	MTF	Line pairs/mm	MTF	Line pairs/mm	MTF
0	______	0	______	0	______
1	______	1	______	1	______
2	______	2	______	2	______
3	______	3	______	3	______
4	______	4	______	4	______
5	______	5	______	5	______
6	______	6	______	6	______
7	______	7	______	7	______
8	______	8	______	8	______
9	______	9	______	9	______
10	______	10	______	10	______
11	______	11	______	11	______
12	______	12	______	12	______
13	______	13	______	13	______
14	______	14	______	14	______
15	______	15	______	15	______

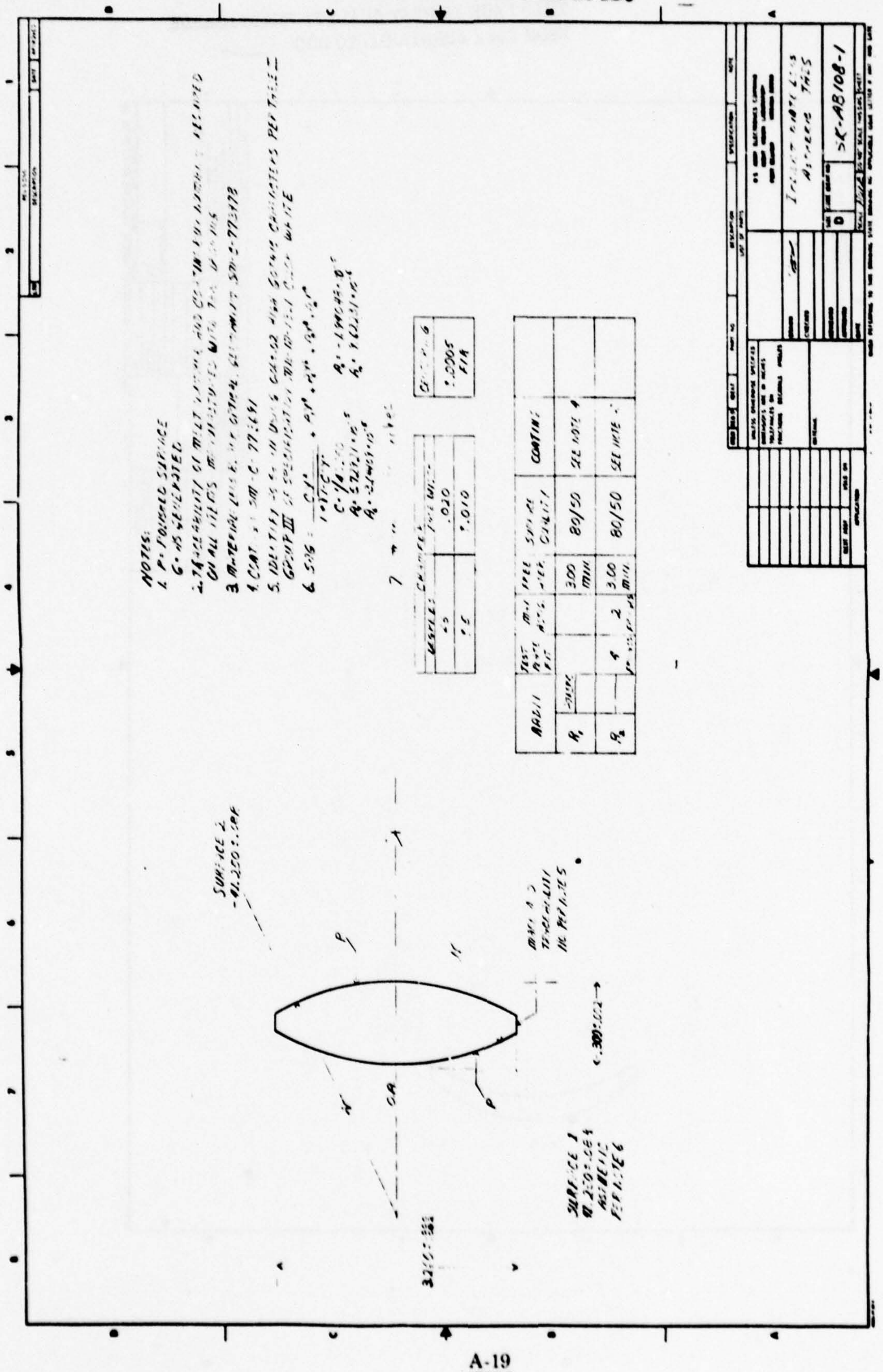
SIZE	CODE IDENT NO	DRAWING NO
A	80063	SM-A-774953

DWG NO ______ SCALE REV SHEET 13

Test Performed By ______________________ Date ______________

SIZE	CODE IDENT NO	DRAWING NO
A	80063	SM-A-774953
SCALE	REV	SHEET 14

D DWG NO ____________


NOTES:
SURFACE 1
SURFACE 2
RADII
COATING
80/50
80/50
SEE NOTE 4
SK-AB108-1

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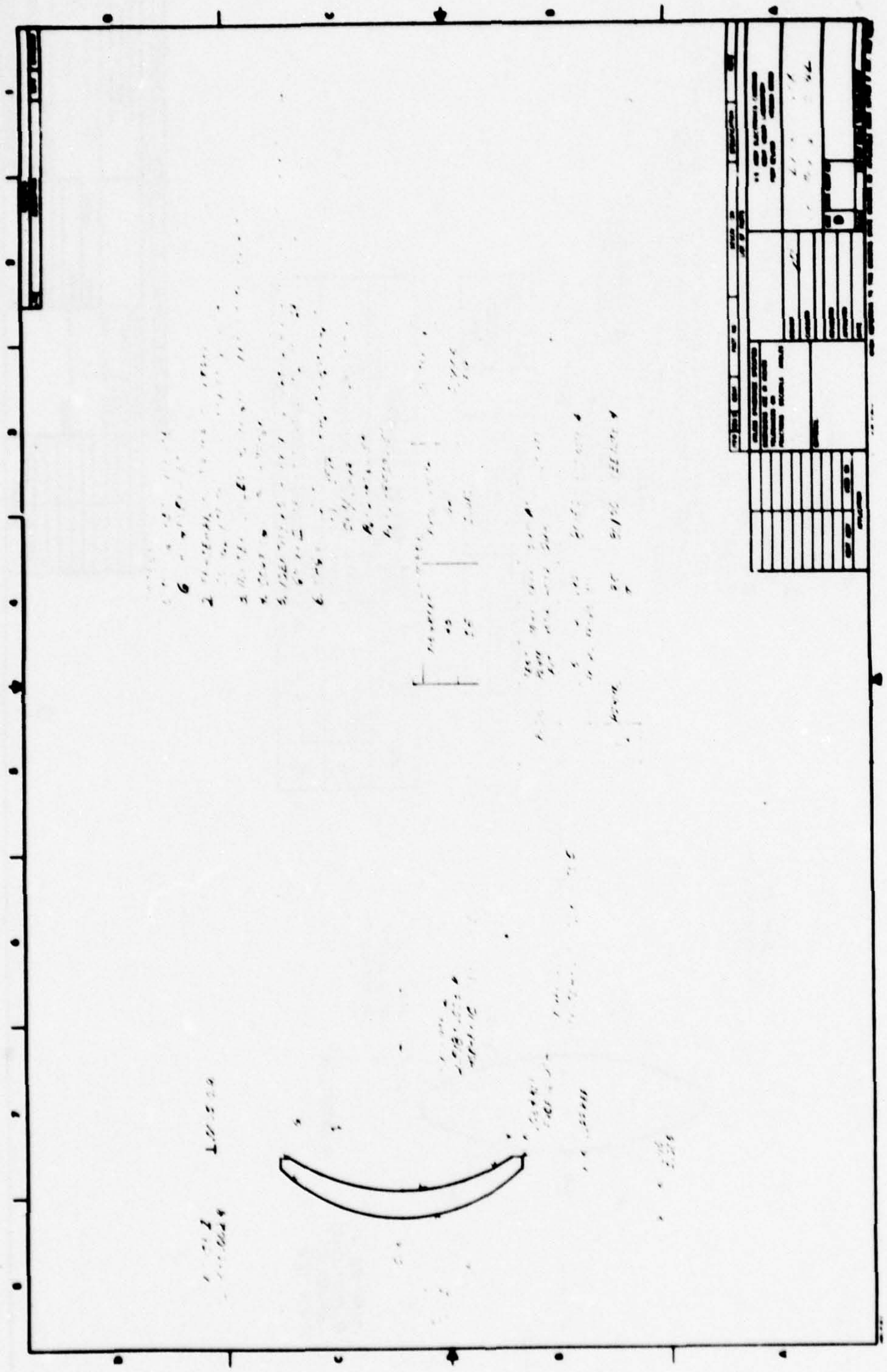

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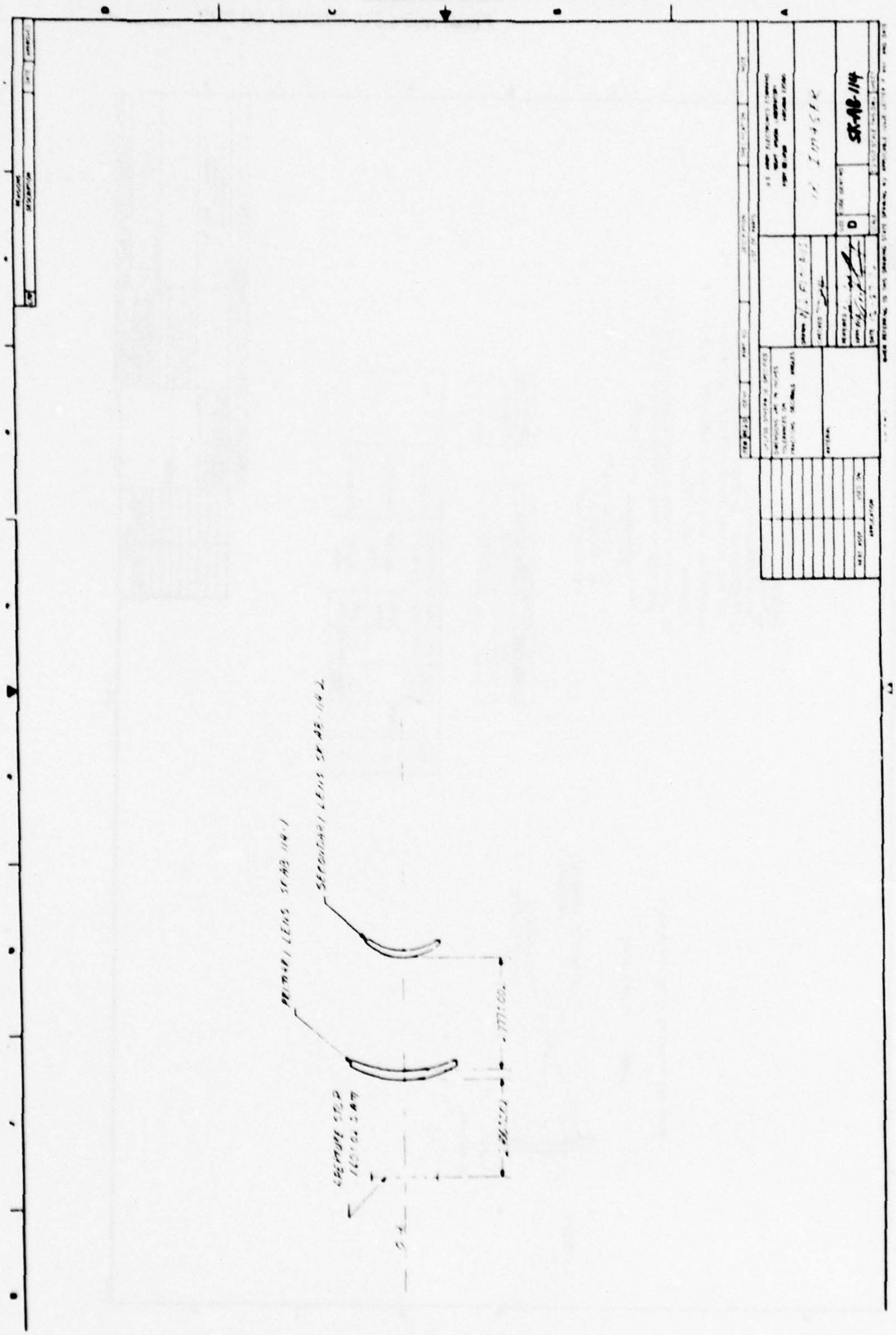
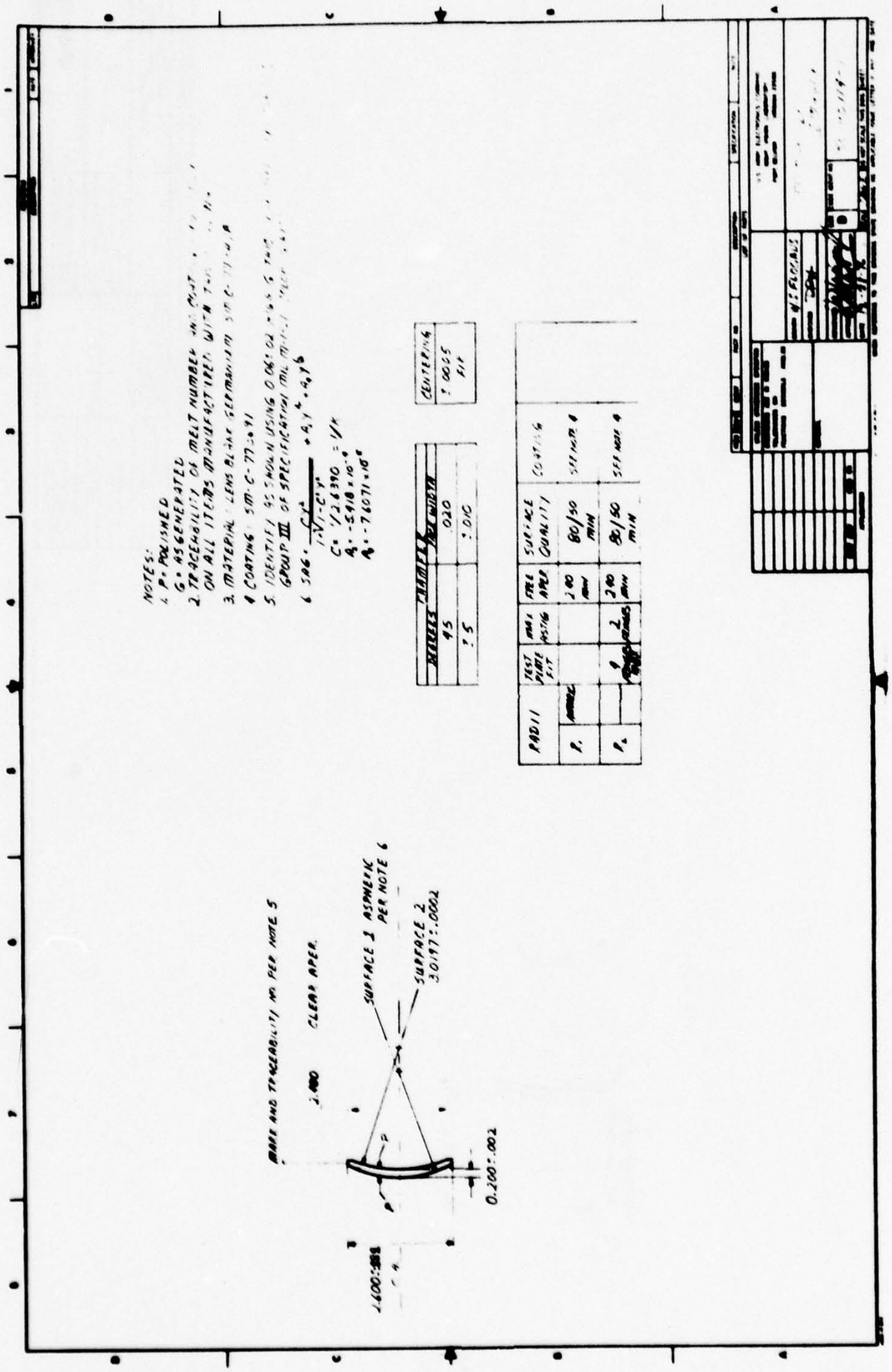
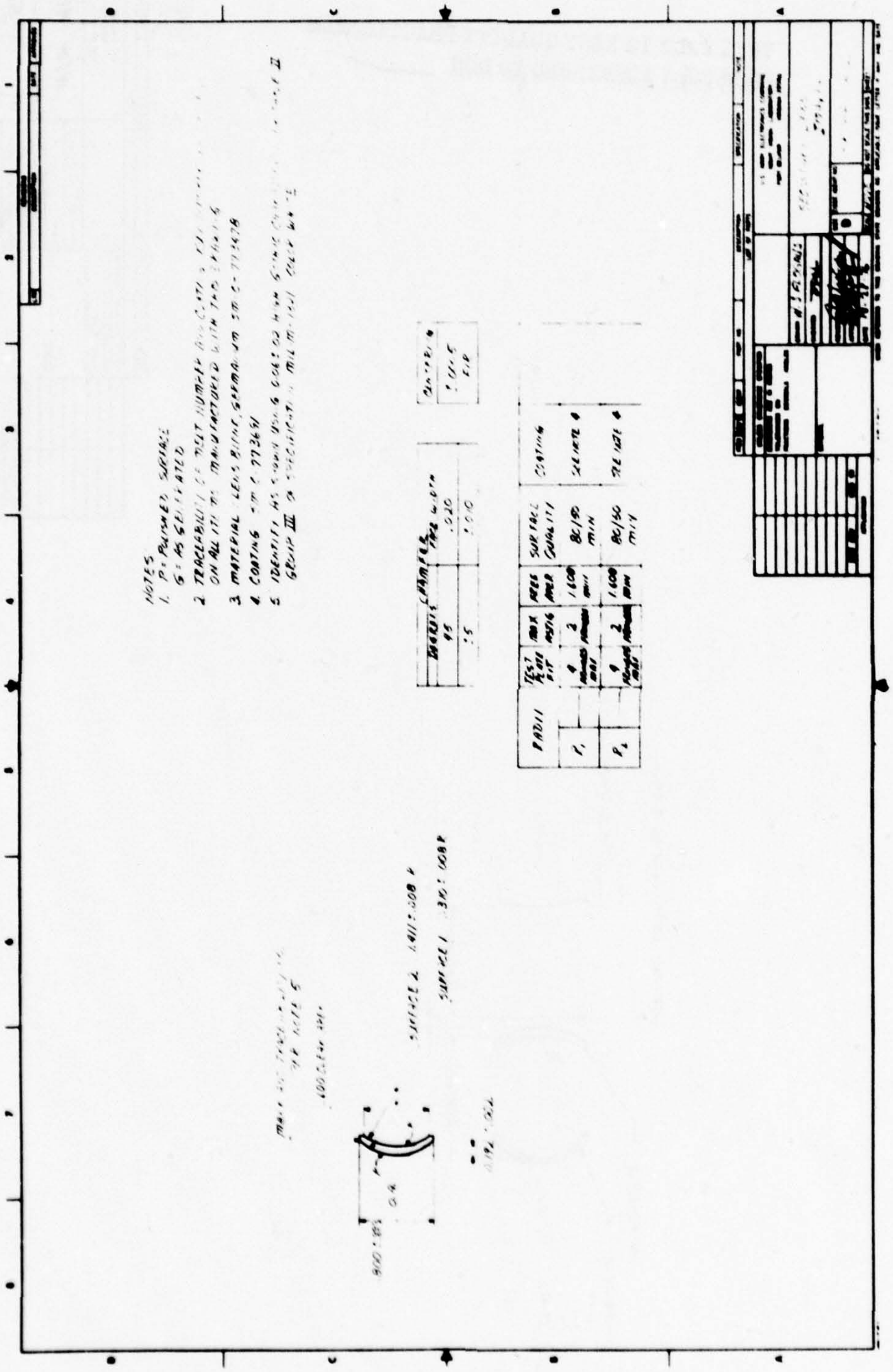
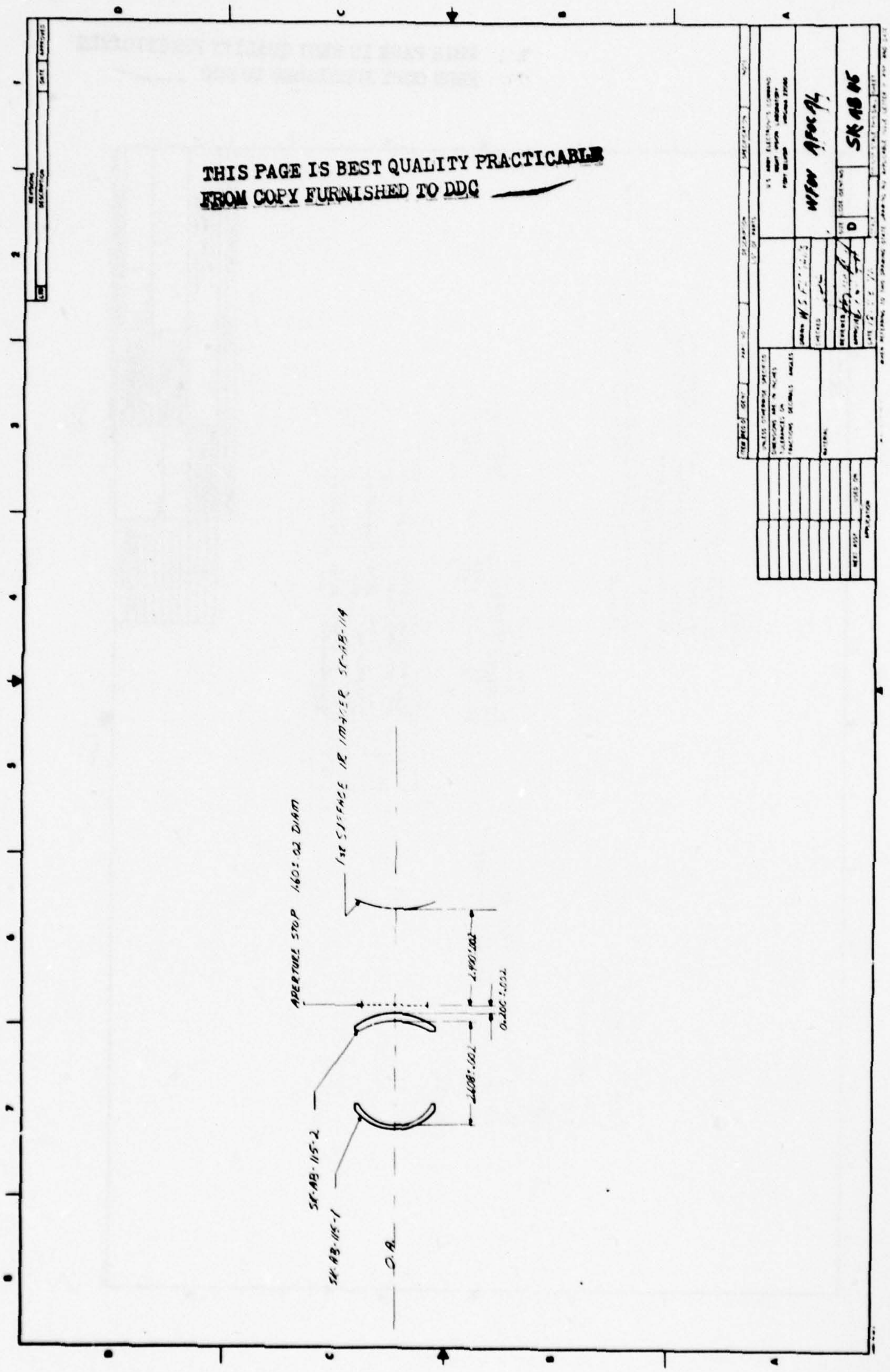





NOTES
1. P = POLISHED SURFACE
G = AS GENERATED
4. COATING
RADII
COATING
SURFACE QUALITY

47356


WFOV AFOCAL
SK AB 116
APERTURE STOP .160±.02 DIAM
1st SURFACE IR IMAGER SK-AB-114
SK-AB-115-2
SK-AB-115-1
O.A.

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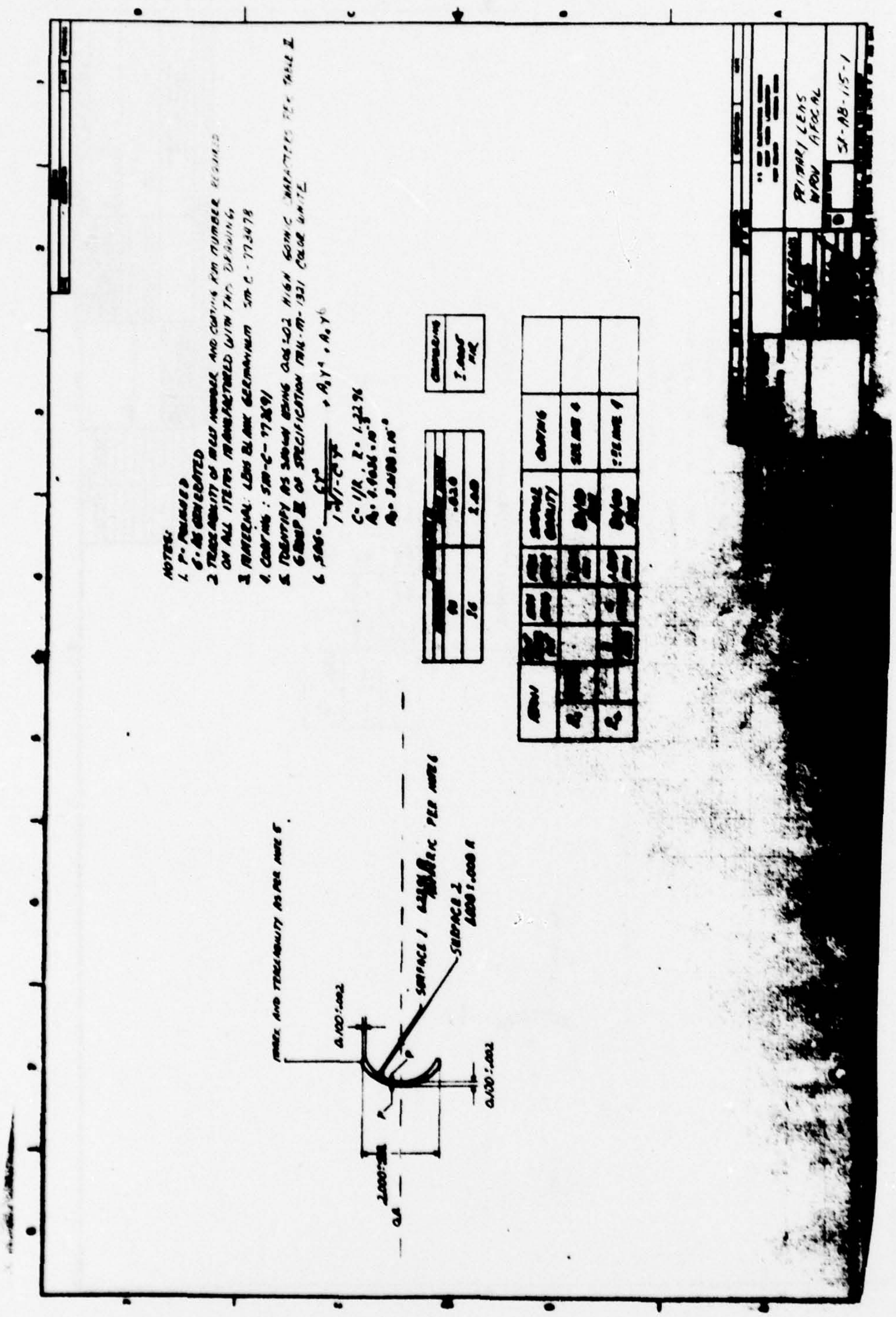

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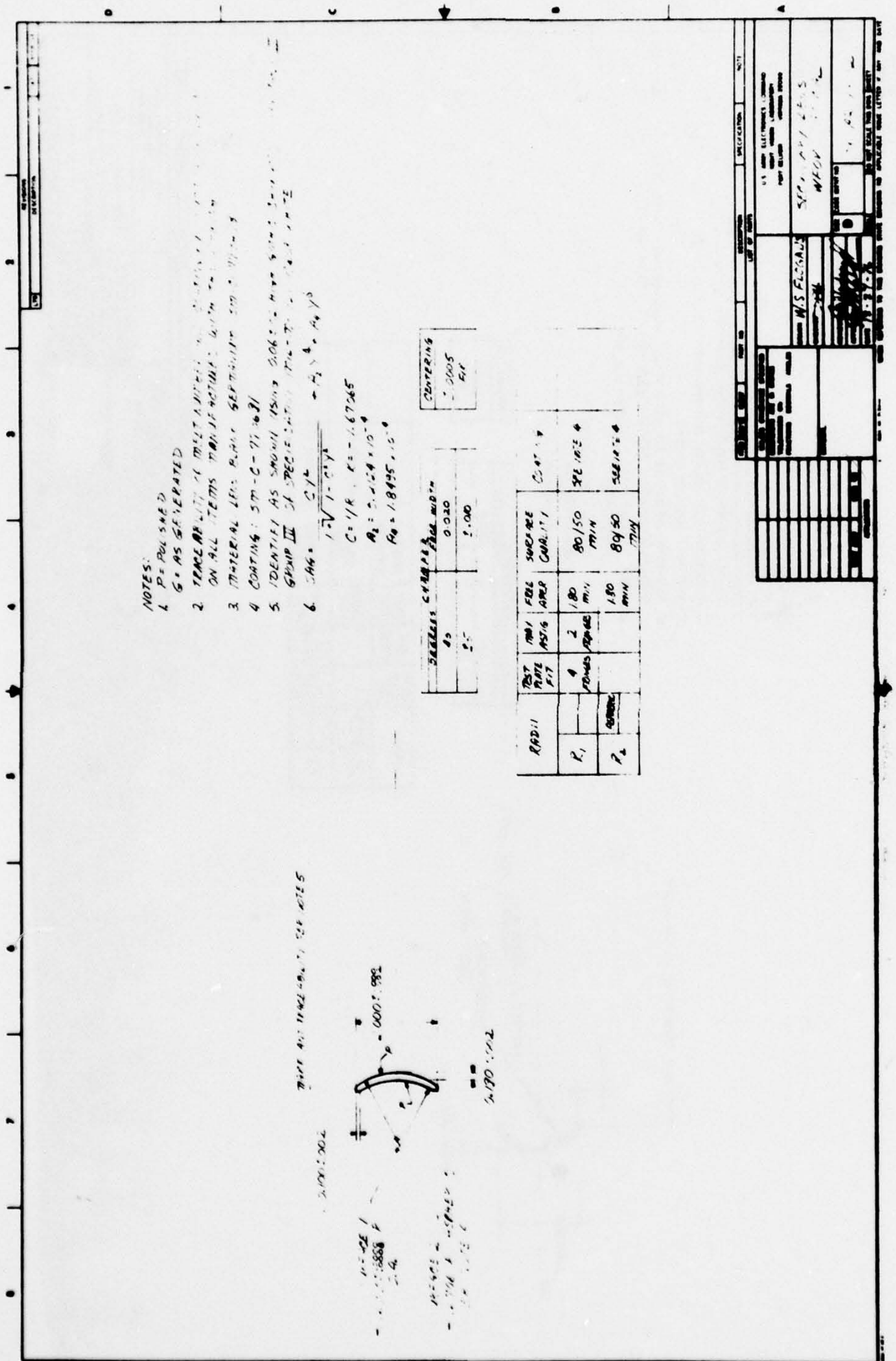

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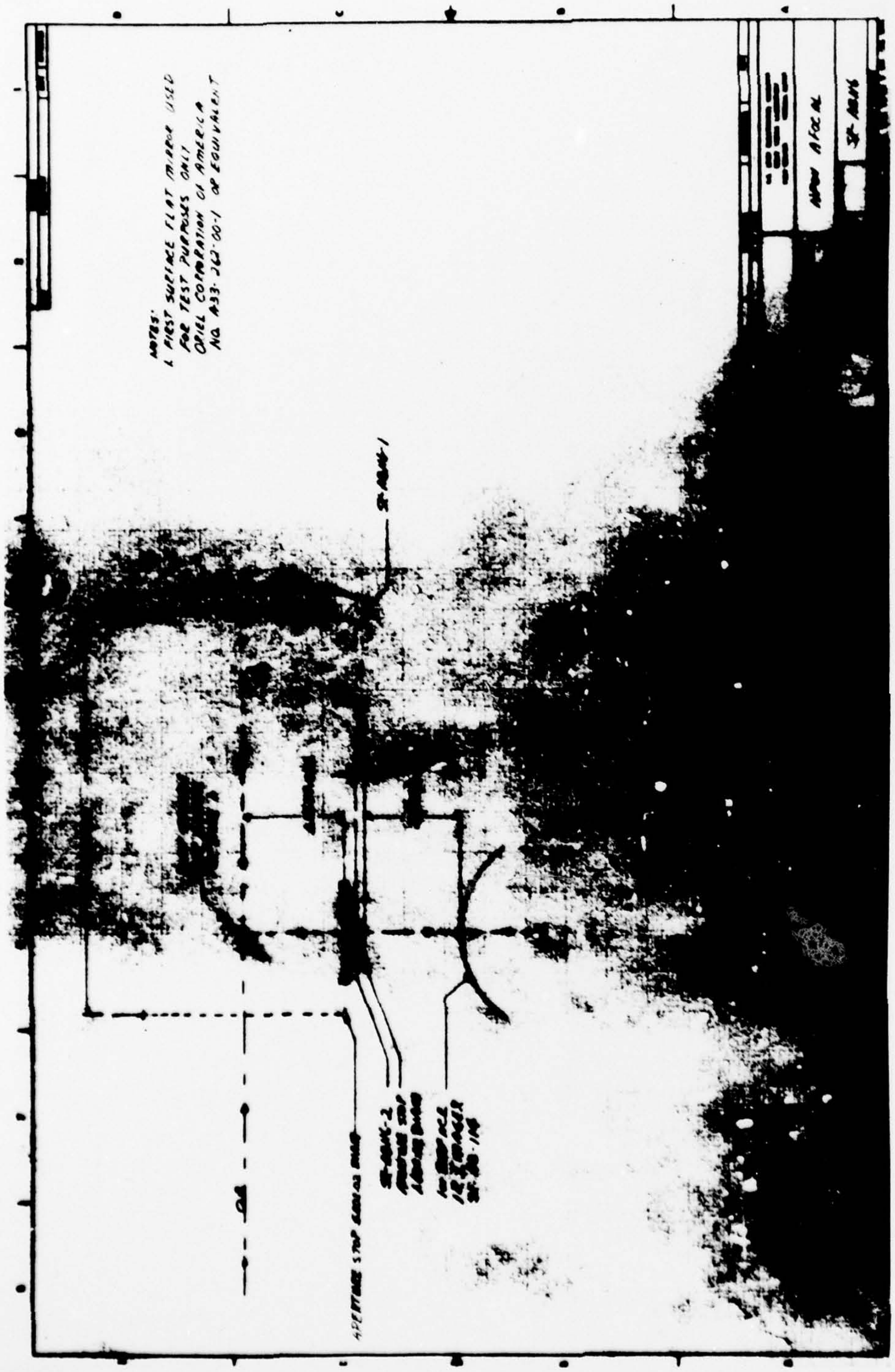
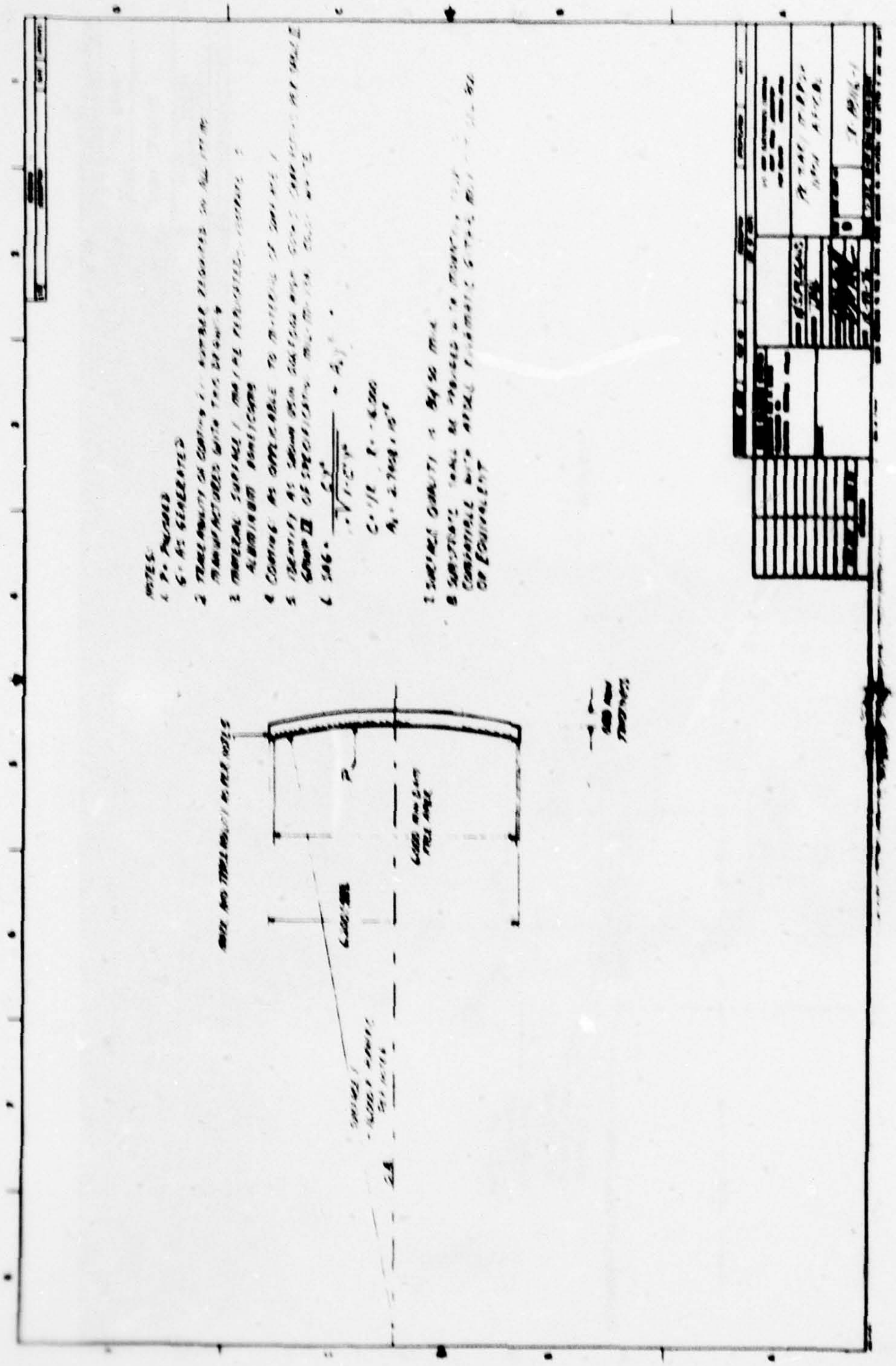
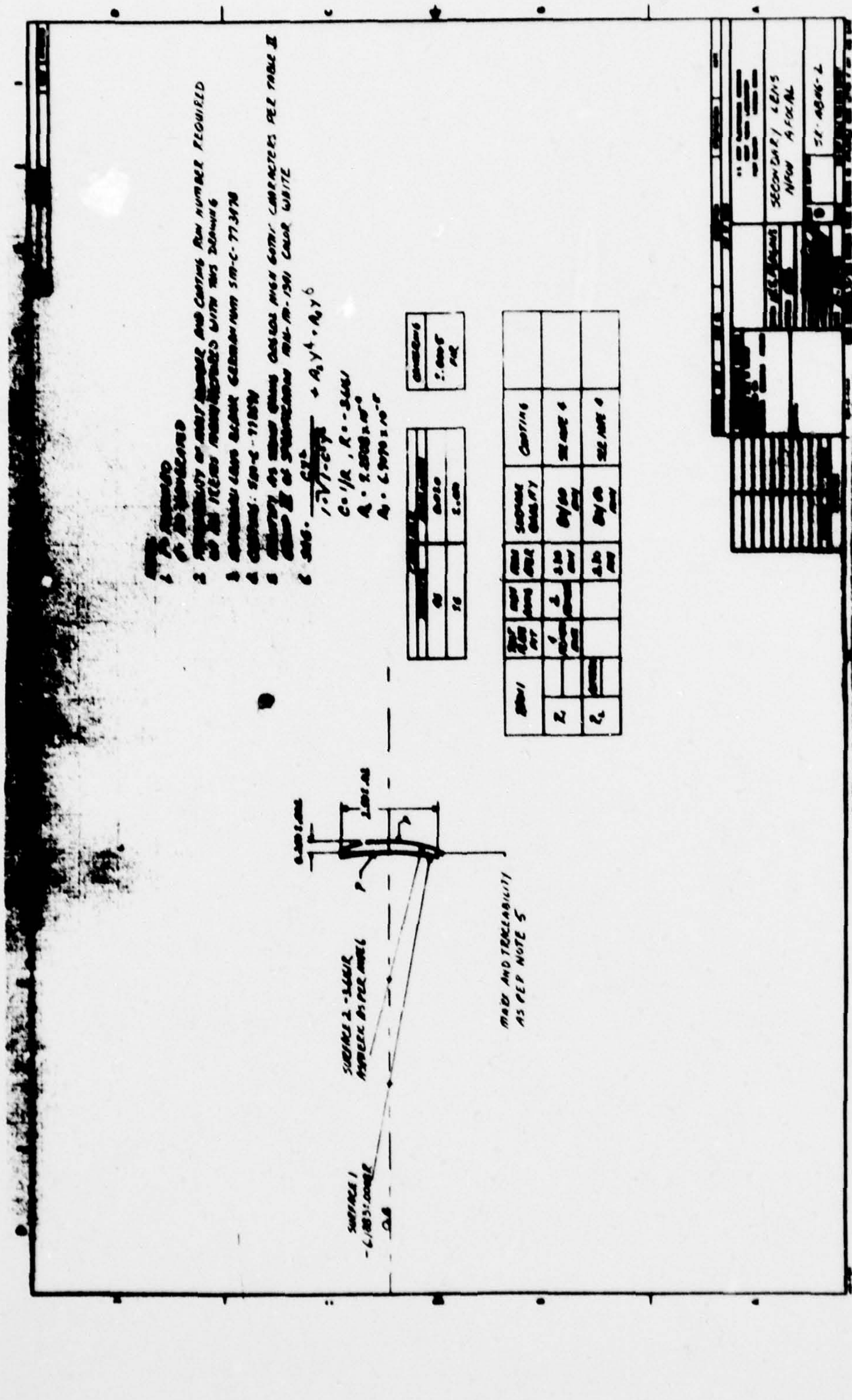

NOTES:
1. FIRST SURFACE FLAT MIRROR USED
FOR TEST PURPOSES ONLY
ORIEL CORPORATION OF AMERICA
NO. A33-263-00-1 OR EQUIVALENT





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Appendix B
High Performance FLIR Lens and Lens Element Specification

HIGH PERFORMANCE FLIR LENS AND LENS ELEMENTS

1. SCOPE

1.1 This specification covers the requirements for lens elements for high performance forward looking infrared (FLIR) objective lenses.

2. APPLICABLE DOCUMENTS

2.1. The following documents, of issue in effect on the date of invitation for bids or request for proposal, form a part of this specification to the extent specified herein.

SPECIFICATIONS

Military

MIL-C-675	Coating of Glass Optical Elements (Anti-Reflection)
MIL-G-174	Glass, Optical
MIL-O-13830	Optical Components for Fire Control Instruments, General Specifications Governing the Manufacture, Assembly, and Inspection of
MIL-O-16898	Optical Elements, Packing of

STANDARDS

MIL-STD-130	Identification Marking of U.S. Military Property
MIL-STD-150	Photographic Lenses
MIL-STD-1241	Optical Terms and Definition

DRAWINGS

SM-C-772326	Label, Radioactivity
SM-C-804148	Lens Blank, Optical Germanium
SM-C-773691	Specification for Multilayer Anti-Reflection (MLAR) Coatings of Infrared Optical Elements

SM-A-774953	Acceptance Test Procedure for Afocal/Cover SU-95/TAS-4
SK-AB 108-1	Intermediate Lens Aspheric TADS
SK-AB 108-2	Lens No. 3X, IR Imaging, Small
SK-AB 114	IR Imager
SK-AB 114-1	Primary Lens, IR Imager
SK-AB 114-2	Secondary Lens, IR Imager
SK-AB 115	WFOV Afocal
SK-AB 115-1	Primary Lens, WFOV Afocal
SK-AB 115-2	Secondary Lens, WFOV Afocal
SK-AB 116	NFOV Afocal
SK-AB 116-1	Primary Mirror, NFOV Afocal
SK-AB 116-2	Secondary Lens, NFOV Afocal

3. REQUIREMENTS

3.1 Item Definitions

The lens elements described in the following drawings comprise two (2) objective lens assemblies and two (2) individual lens elements.

3.1.1 Objective Assembly A:

SK-AB 115
SK-AB 114

3.1.2 Objective Assembly B:

SK-AB 116
SK-AB 114

3.1.3 Individual Elements:

Element C	SK.AB 108-1
Element D	SK.AB 108-2

3.2 Design and Construction The objective assemblies and individual elements listed in paragraph 3.1 shall conform to the mechanical dimensions and optical data specified on the drawings. Lens elements coatings shall conform to the applicable drawing and to drawing SM-C-773691. The lens element materials shall conform to the applicable drawing and to drawings SM-C-773477, SM-C-773478, and SM-C-804142. (See 4.3.1)

3.3 Edge chips Edge chips and fractures shall be in accordance with the requirement "Edge chips" of MIL-O-13830 as applied to "Lenses". (See 4.3.3)

3.4 Surface quality The scratches and digs as defined by MIL-O-13830 shall be in conformance with the applicable drawing. Coating scratches shall be in accordance with "Coating scratches" of MIL-O-13830 and "Coating process" and "Surface quality" of MIL-C-675. (See 4.3.2)

3.5 Handling During handling, shipping, and storage, all optical elements shall be protected from physical damage to the material or coatings by clean, lint-free packaging materials. During assembly, white, lint-free gloves shall be worn to prevent leaving fingerprints or foreign material on the elements which will degrade the optical properties or deteriorate the coatings. (See 4.3.5)

3.6 Performance The characteristics of an afocal optical system require that all measurements of performance characteristics be made in combination with an auxiliary imaging lens.

3.6.1 Objective Assembly A. The requirements of the following paragraphs are based on conformance to the drawings listed in 3.1.1 and on conformance to the other applicable requirements of this specification for an 18 millimeter diameter format.

3.6.1.1 Field of view The field of view of the WFOV optical system shall be 30.0 ± 0.4 degrees (See 4.3.7)

3.6.1.2 Aperture The clear aperture of the elements shall be as specified on the relevant drawings. (See 4.3.8)

3.6.1.3 Modulation transfer function (MTF) The objective shall provide an MTF which is greater than that shown in Figure 1. (See 4.3.9)

3.6.1.4 Linear distortion The linear distortion of the objective assembly shall be between 4-percent pincushion and 4-percent barrel. (See 4.3.10)

3.6.1.5 Optical transmittance The average optical transmittance of the objective assembly, in the 8 to 12 micrometer region, shall be greater than 83 percent. (See 4.3.11)

3.6.2 Objective Assembly B The requirements of the following paragraphs are based on conformance to the drawings listed in 3.1.1, and on conformance to the other applicable requirements of this specification for an 18 millimeter diameter format.

3.6.2.1 Field of view The field of view of the optical system shall be 5.0 ± 0.4 degrees. (See 4.3.7)

3.6.2.2 Aperture The clear aperture of the lens elements shall be as specified on the relevant drawings. (See 4.3.8)

3.6.2.3 Modulation transfer function The objective lens assembly shall provide an MTF which is equal to or greater than that specified in Figure 1. (See 4.3.9)

3.6.2.4 Linear distortion The linear distortion of the objective assembly shall be between 4-percent pincushion and 4-percent barrel. (See 4.3.10).

3.6.2.5 Optical transmittance The average optical transmittance in the 8 to 12 micrometer range of the objective assembly in the NFOV shall be greater than 79 percent. (See 4.3.11)

3.7 Workmanship All details of workmanship shall be in accordance with high grade optical manufacturing practice. (See 4.3.4)

3.8 Environmental conditions

3.8.1 Adherence and Abrasion There shall be no visible damage to the area of a coated surface used for the adherence test or to the rubbed area of a coated surface after being subjected to the "adherence and abrasion" tests specified in drawing SM-C-773691. (See 4.3.12)

3.8.2 Humidity There shall be no visible evidence of film deterioration after being subjected to the conditions specified for "humidity" tests in drawing SM-C-773691. (See 4.3.13)

3.8.3 Salt spray (fog) There shall be no visible evidence of film deterioration after the coated optical element has been subjected to the test specified in drawing SM-C-773691. (See 4.3.14)

3.9 Identification and marking Each element (including those belonging to objective assemblies) shall be individually marked in accordance with the applicable drawing with the drawing number for the element, type of material, material melt number and coating run number, and manufacturer's name or code symbol. Each element shall be individually bagged and the bag marked in accordance with MIL-STD-130 with the above data. The radioactivity label, as required, described in drawing SM-C-772326, shall be firmly affixed to the bag. (See 4.3.6)

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4. QUALITY ASSURANCE PROVISIONS

4.1 Responsibility for inspection Unless otherwise specified in the contract or purchase order the supplier is responsible for the performance of all inspection requirements as specified herein. Except as otherwise specified, the supplier may use his own or any other facilities suitable for the performance of the inspection requirements specified herein. Inspection records of the examinations and tests shall be kept complete and available to the Government as specified in the contract. The Government reserves the right to perform any of the inspections set forth in the purchase description where such inspections are deemed necessary to assure that supplies and services conform to the prescribed requirements.

4.1.1 Test Plan The contractor prepared Government-approved test plan as cited in the contract, shall contain:

(a) Time schedule and sequence of examinations and tests.

(b) A complete description of the method of test and procedures.

(c) Complete identification and description of each inspection instrument and date of most recent calibration.

4.2 Inspection conditions Unless otherwise specified, all inspections shall be performed in accordance with the test conditions specified in 4.6. All test methods wherein latitude is granted in test details due to variability of approach and test facilities require Government approval prior to initiation of any testing.

4.3 Test procedures

4.3.1 Design and Construction For spherical surfaces, standard optical surface test plates shall be placed in contact with the subject element and the difference in surface accuracy and radii is determined by the interference fringes found. The radius difference ΔR, can be calculated by $\Delta R = N \lambda (2R/d)^2$, where N is the number of fringes, λ is the illumination wavelength, R is the radius of the test plate, and d is the diameter over which the measurement is made. Surface accuracy is determined by visually examining local areas of the interference rings for deviations from circular shape. For aspherical surfaces the Foucault knife edge test shall be used to determine the differences between measured foci values and calculated foci values from the equation for the aspheric surface for various zones across the element. (See 3.2)

4.3.2 Surface quality Surface quality shall be measured by comparison to a standard set of graded defect[illegible]s in test procedures for "surface quality", MIL-O-13830, and "Coating proc[illegible] and "Surface quality" of MIL-C-675. (See 3.4)

4.3.3 Edge Chips Each element shall be inspected visually in diffuse illumination of normal intensity. Chip dimensions shall be measured with standard measuring equipment. (See 3.3)

4.3.4 Workmanship The fabrication processes, facilities and final end item elements and objective assemblies shall be observed and inspected for conformance to the requirements. (See 3.7)

4.3.5 Handling The packing materials and storage areas shall be inspected to verify adequate precautions against physical damage to the lens materials and coatings. Observations of the handling techniques shall be made to determine that proper safeguards are being used to prevent contamination of the lens elements or assemblies as specified herein. (See 3.5)

4.3.6 Identification and marking The elements shall be visually inspected to verify that the markings are in accordance with the applicable requirements and drawings. (See 3.9)

4.3.7 Field of view The field of view of the objective assembly shall be measured in conjunction with the linear (para. 4.3.10) distortion test over the format size specified. (See 3.6.1.1, 3.6.2.1)

4.3.8 Aperture The exposed clear aperture of the objective assembly shall be measured using Method 3 of MIL-STD-150A. Pupil diameters shall be established by ray trace analysis. (See 3.6.1.2, 3.6.2.2)

4.3.9 Modulation transfer function (MTF) The MTF of each objective assembly shall be measured using a test set and methods similar to that shown in drawing SM-A-774953, "modulation transfer function" section. The MTF shall be measured either continuously or in 15 discrete steps between 0 and 15 line pairs per millimeter. The MTF test shall be run at infinite conjugates. Off-axis measurements shall be made in the same plane as that chosen for the on-axis image, and shall correspond to an image translation parallel to the long dimension of the detector array. The lens elements comprising an assembly shall be mounted only in test lens holders. (See 3.6.1.3, 3.6.2.3)

4.3.10 Linear distortion The linear distortion of the objective assembly shall be measured using either Method 25 or Method 28 of MIL-STD-150A, substituting a suitable detector for the spectral region of interest for the microscope. (See 3.6.1.4, 3.6.2.4)

4.3.11 Optical transmittance The optical transmittance of the objective assembly will not be measured directly. Coated witness samples from each run of lenses will be measured for transmittance. From these data, the overall transmittance will be calculated. (See 3.6.1.5, 3.6.2.5)

4.3.12 Adherence and abrasion The adherence and abrasion resistance shall be measured as required by drawing SC-M-773691. (See 3.8.1)

4.3.13 Humidity The humidity resistance shall be measured as required by drawing SC-M-773691. (See 3.8.2)

4.3.14 Salt spray (fog) The salt spray (fog) resistance shall be measured as required by drawing SC-M-773691. (See 3.8.3)

Appendix C
Distribution List